Longitudinal Optimizations for Space Charge Reduction in the CERN PSB

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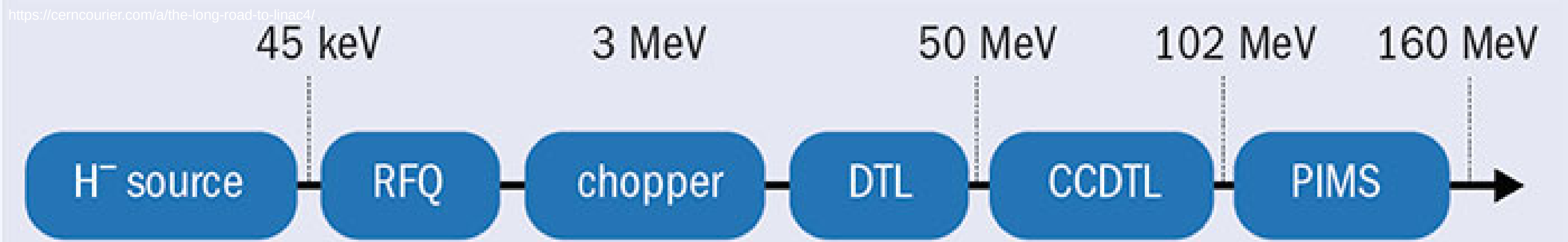
With thanks to A. Akroh, M. E. Angoletta, F. Antoniou, B. Bielawski, H. Damerau, A. Findlay, G. P. Di Giovanni, P. Skowronski, R. Wegner, all involved in Linac4 and PSB operation

Contents

- Overview of Linac4 and the PSB
- Influence of RF Settings on Transverse Space Charge
- Machine Learning for RF Capture Optimisation
- Triple Harmonic Capture
- Longitudinal Painting
- Conclusion

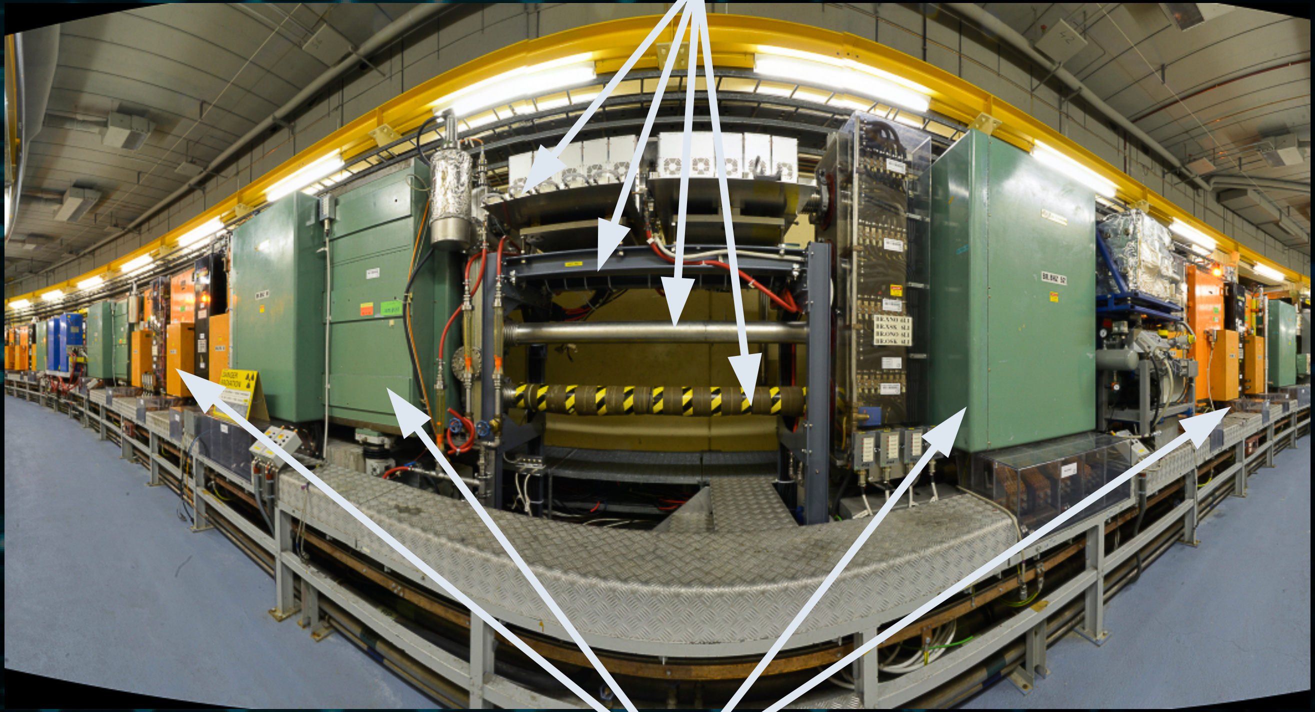
Linac4



- Linac4 uses an H^- ion source for charge exchange injection
- The 800 μs pulse is chopped for bunch-to-bucket transfer
- Up-to 150 turns can be injected at 160 MeV (kinetic energy) to each Proton Synchrotron Booster (PSB) ring
- The last Pi-Mode Structure (PIMS) cavity allows for energy modulation
- A debuncher cavity gives tunable energy spread at PSB injection

PSB

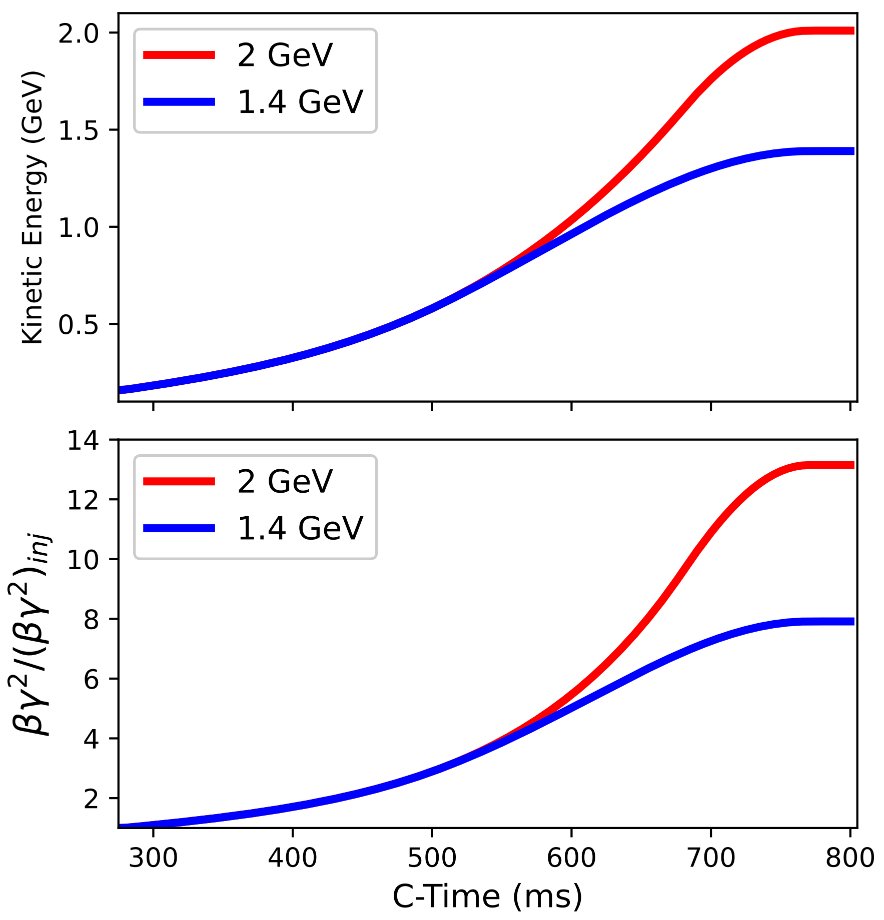
Four semi-independent rings



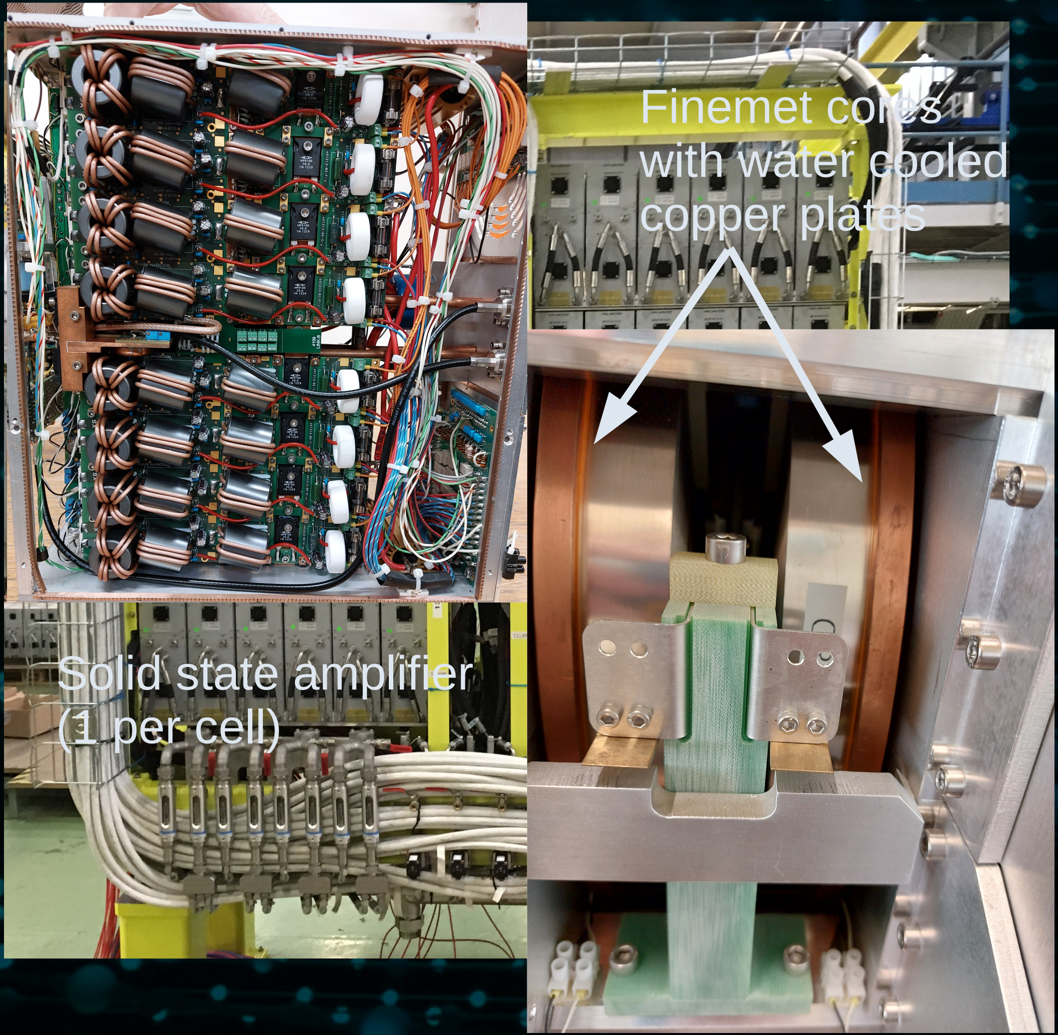
Common main magnets

PSB - Cycle

- Two operational magnetic cycles extract at 1.4 GeV and 2 GeV kinetic energy (other energies are available)
- The first half of the acceleration is the same in both cases
- Injection is 275 ms after start cycle, extraction is 805 ms after start cycle
- After about 200 ms, $\beta\gamma^2$ has doubled



PSB - RF



- Each ring has 3 identical Finemet cavities operating in the frequency range 1 → 18 MHz
- The cavities are loaded with Finemet magnetic alloy, which gives very broadband impedance ($Q \approx 1$)
- Each cavity can simultaneously hold an arbitrary combination of RF harmonics

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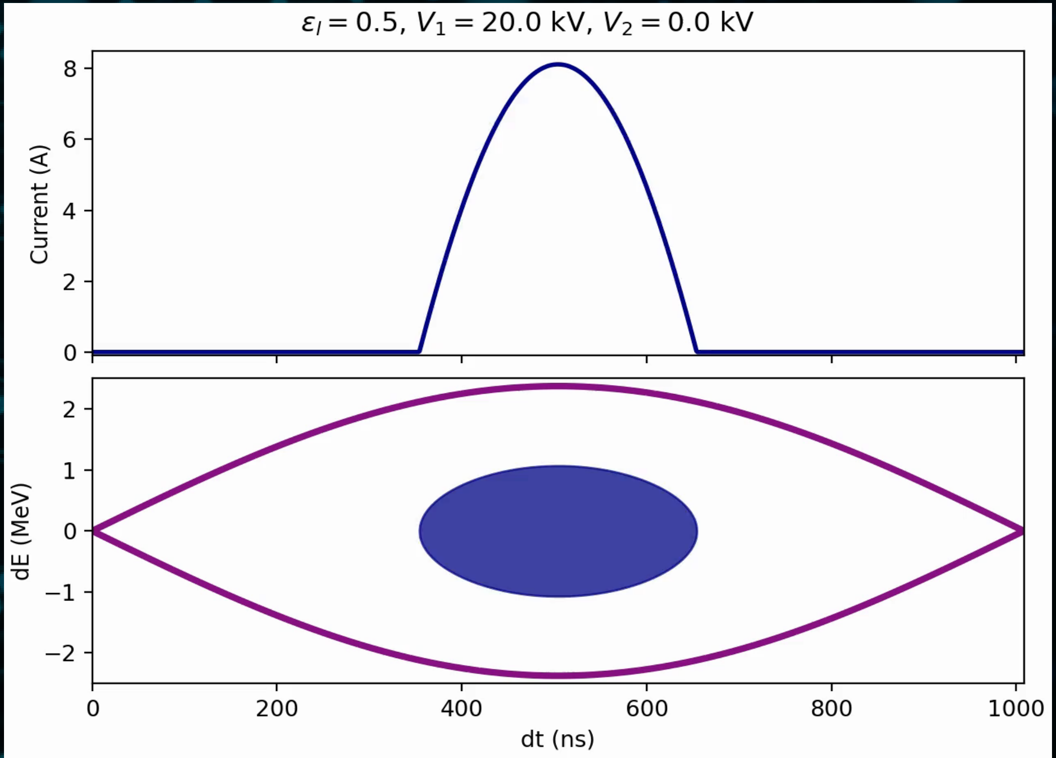
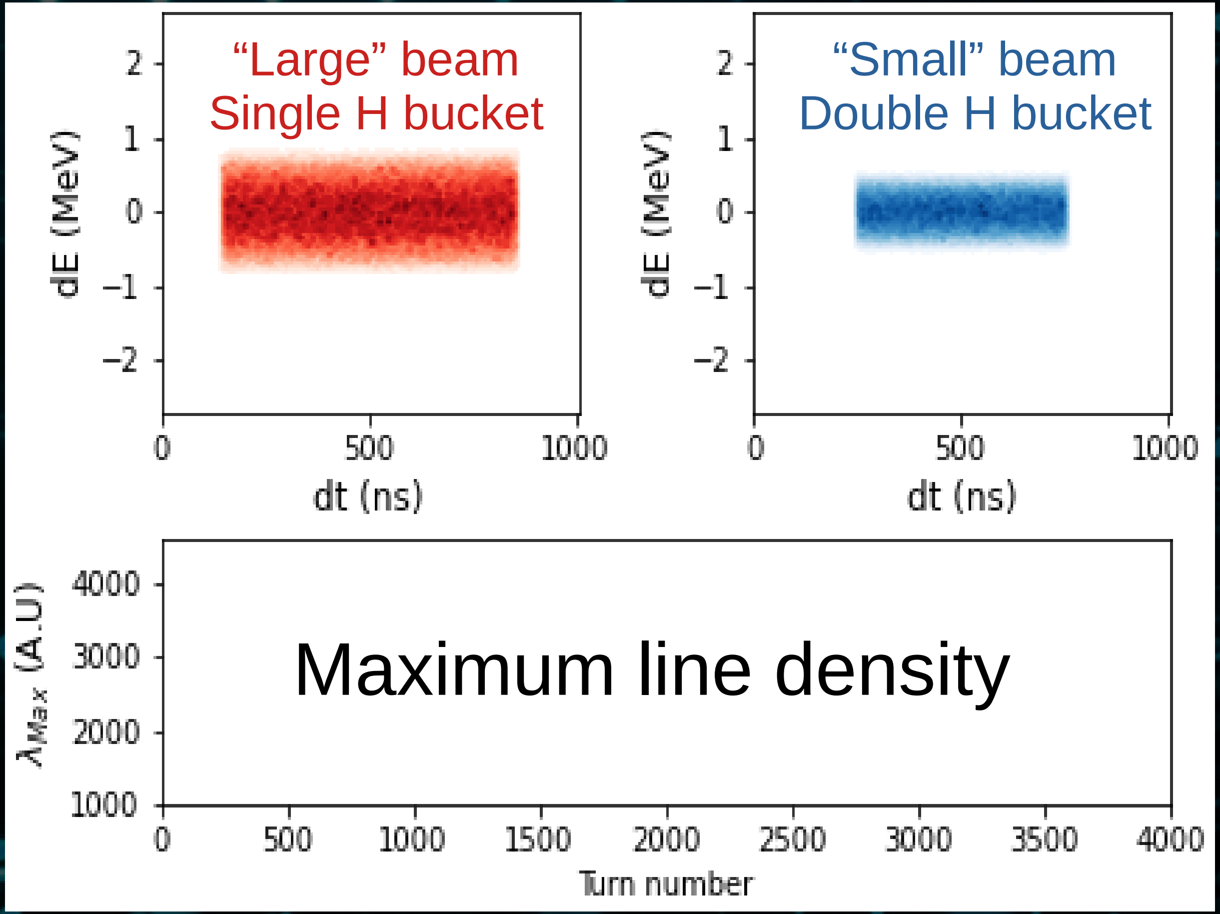
Line Density Reduction

- Generally, the objective is to reduce peak current
- Assuming a matched bunch and constant total voltage, we can:
  - Increase the longitudinal emittance
  - Reshape the potential well
- All else being equal, this is sufficient to significantly reduce transverse space charge

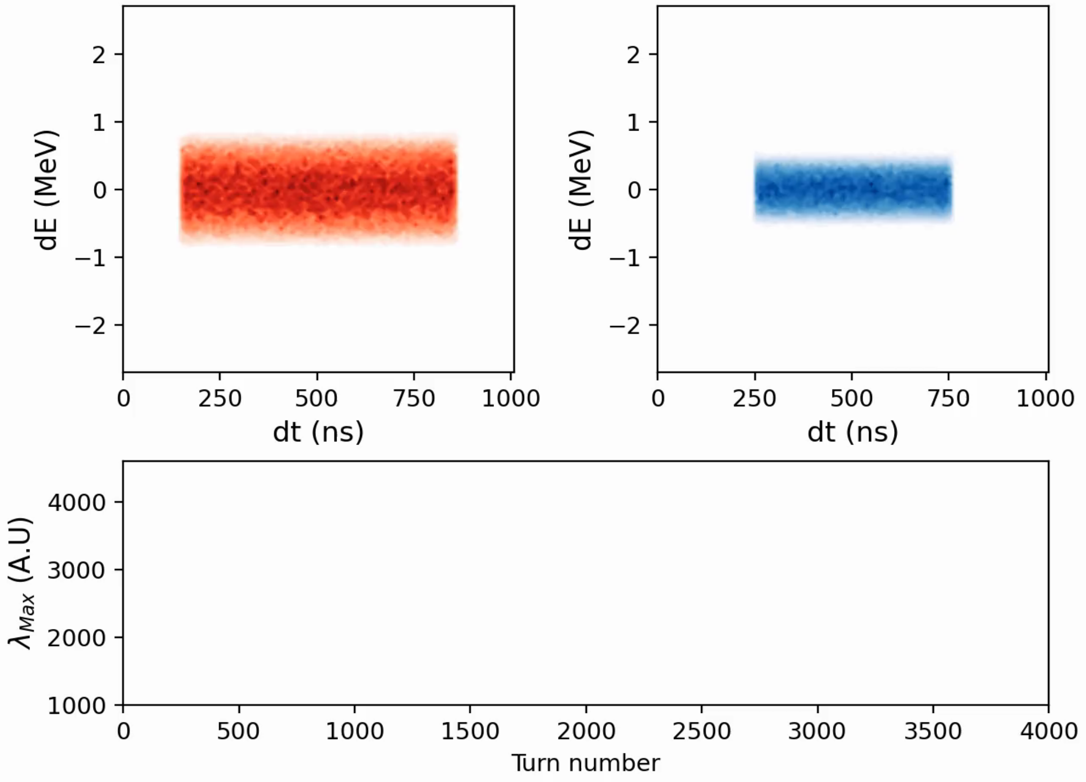


Injection Parameters



- The injected beam is approximately rectangular in longitudinal phase space

Injection Parameters

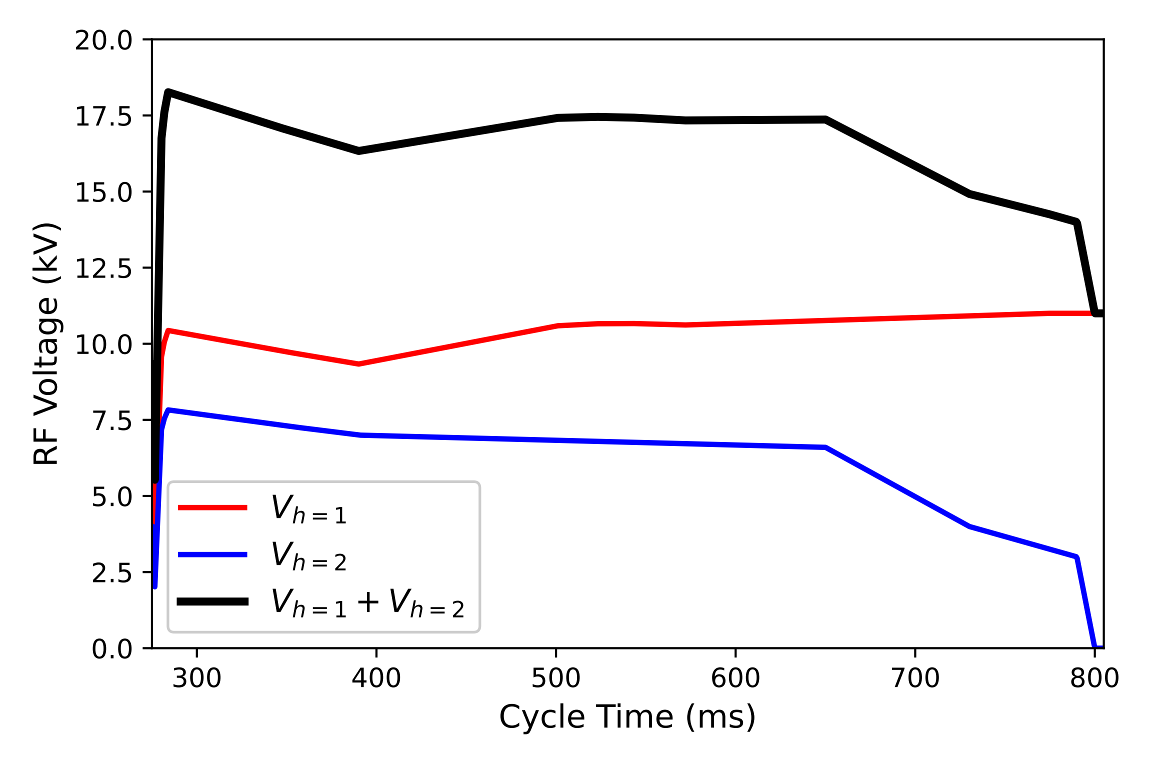


- The injected beam is approximately rectangular in longitudinal phase space
- The peak line density (λ_{max}) is determined by what is injected and how it filaments
- Not obvious how to define the optimum injection parameters

Contents

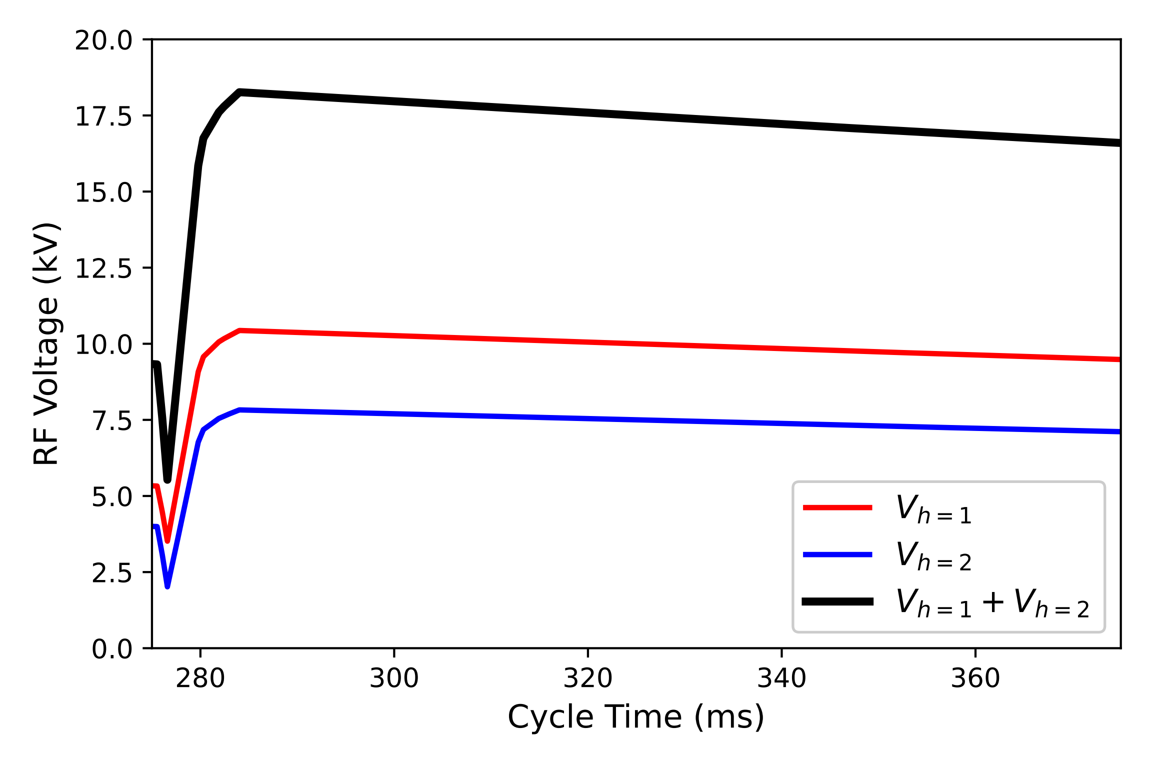
RF Voltage

- Total voltage must stay below 20 kV for the full cycle



RF Voltage

- Total voltage must stay below 20 kV for the full cycle
- Shape of the functions is a product of following the acceleration
- Sum and ratio are free parameters



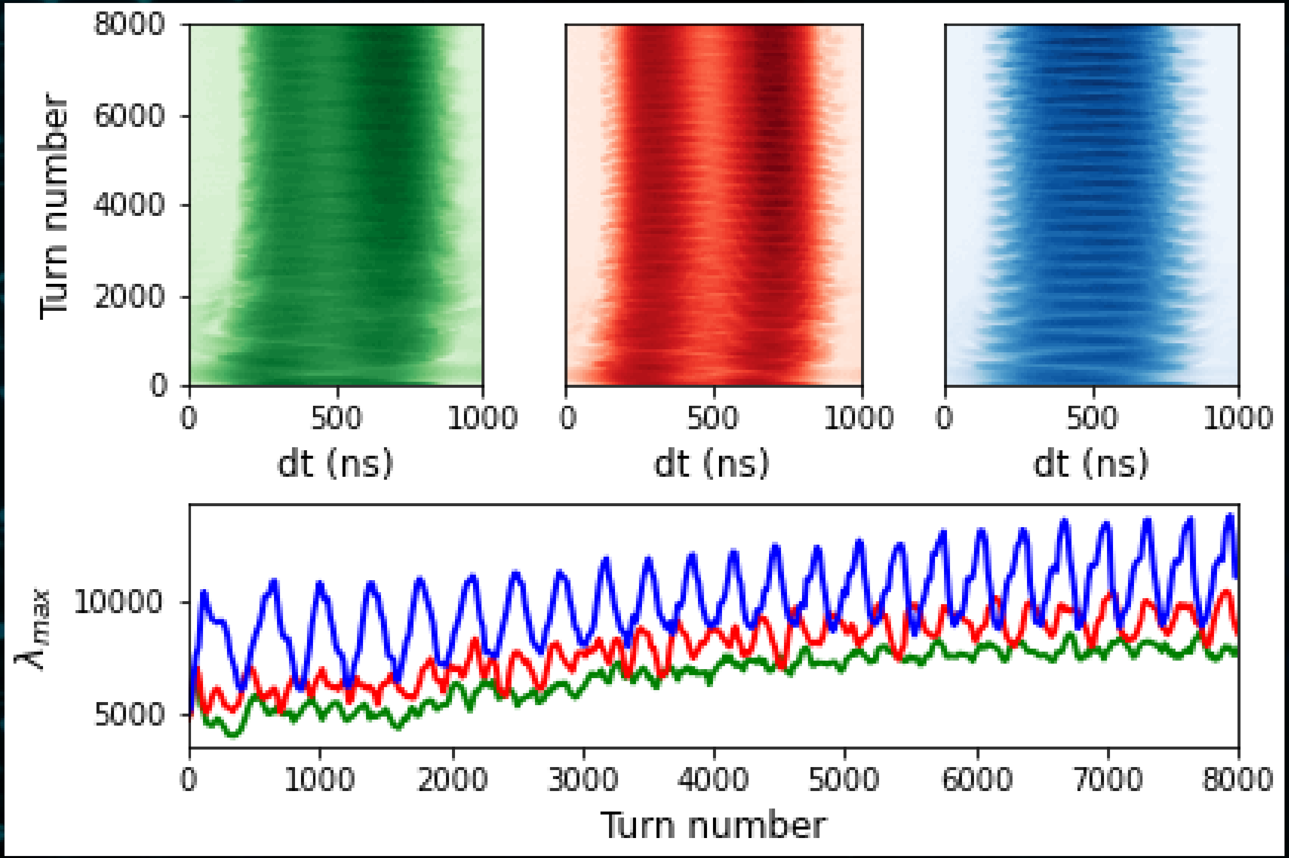
Effect of RF Voltage

- Measurements with fixed injection parameters
- Varied PSB RF voltage at 1st and 2nd harmonic
- Strong influence on the amount of filamentation and the line density
- Clear effect on extracted vertical emittance

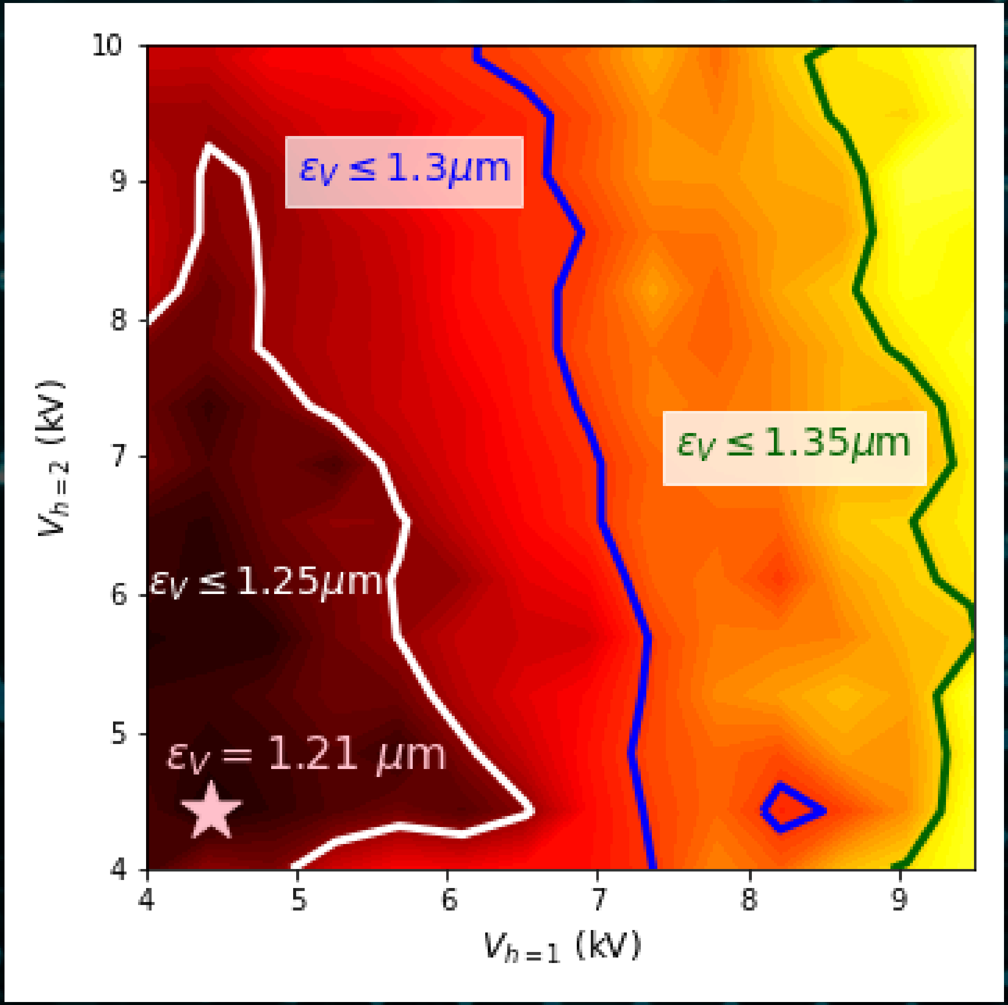
$V_{h=1}:V_{h=2}$ = 4.3kV:4.3kV
ε_V=1.21 μm

$V_{h=1}:V_{h=2}$ = 5.9kV:10kV
ε_V=1.34 μm

$V_{h=1}:V_{h=2}$ = 10kV:5kV
ε_V=1.41 μm



PSB RF Parameter Space

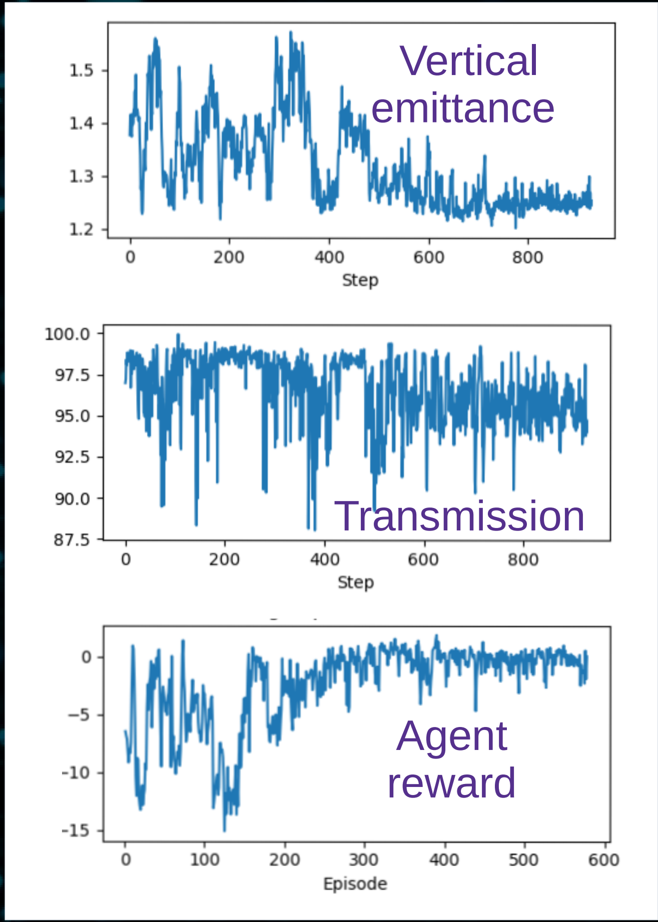


- Parametric scan of vertical emittance at extraction as a function of $V_{h=1}$ and $V_{h=2}$
- Clear global optimum with smooth gradient, ideal for numerical optimization

Reinforcement Learning

- Initial tests were done with fixed injection parameters and only varying the RF voltages
- Both classical optimisation and reinforcement learning are being explored
- RL shows promise over classical optimization for speed and efficacy
- The relative weighting of emittance and transmission defines the reward
- Linac4 parameters (energy spread, bunch length) to be included in the future

Soft-Actor-Critic training



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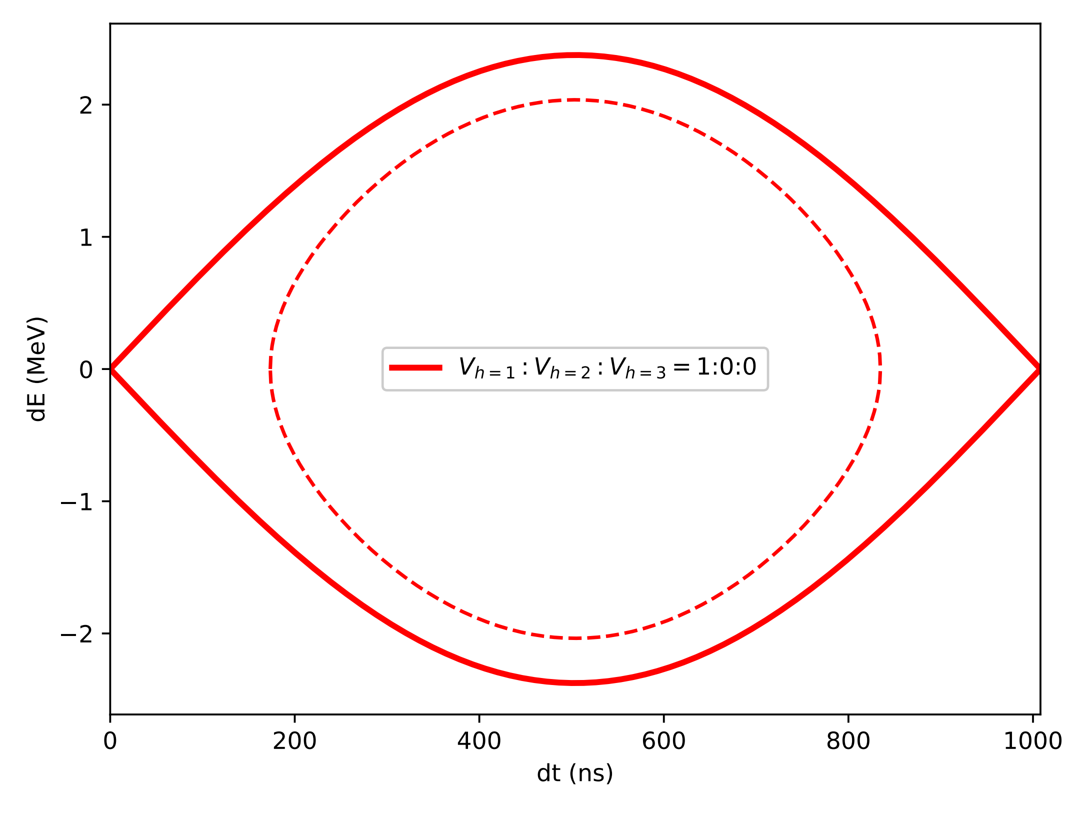
Triple Harmonic Capture

- Bunch lengthening with the 2nd RF harmonic is commonly used



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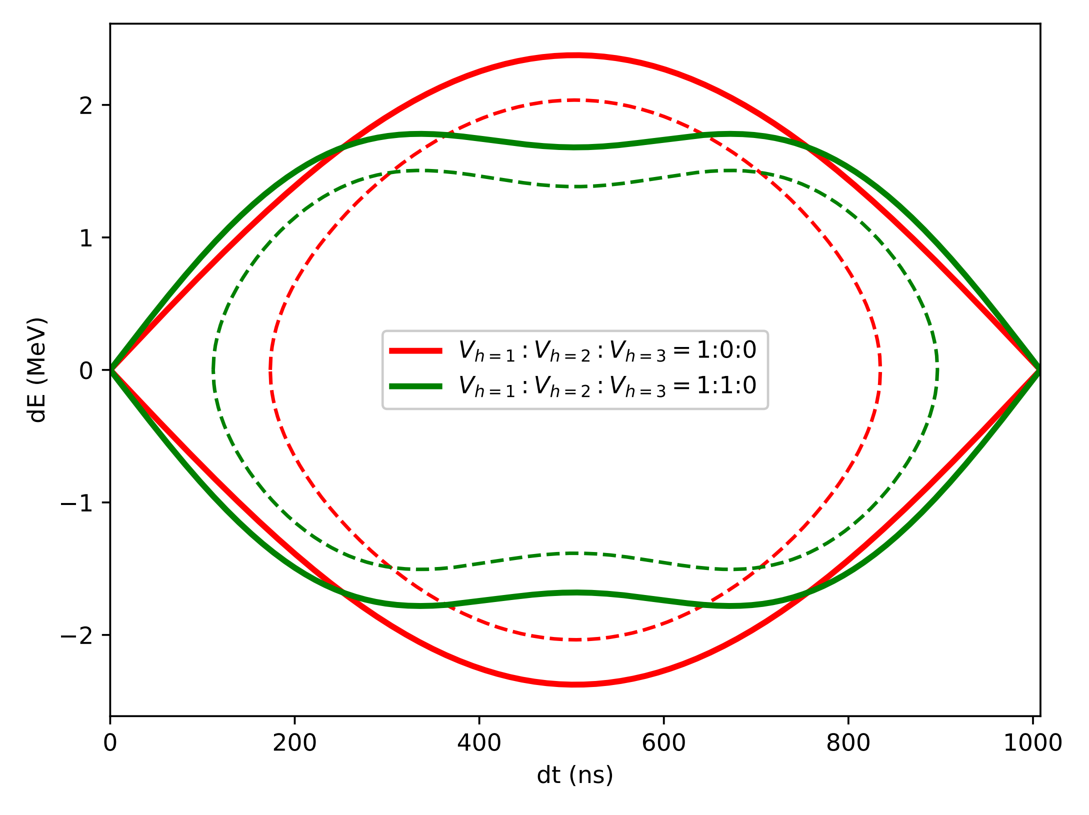
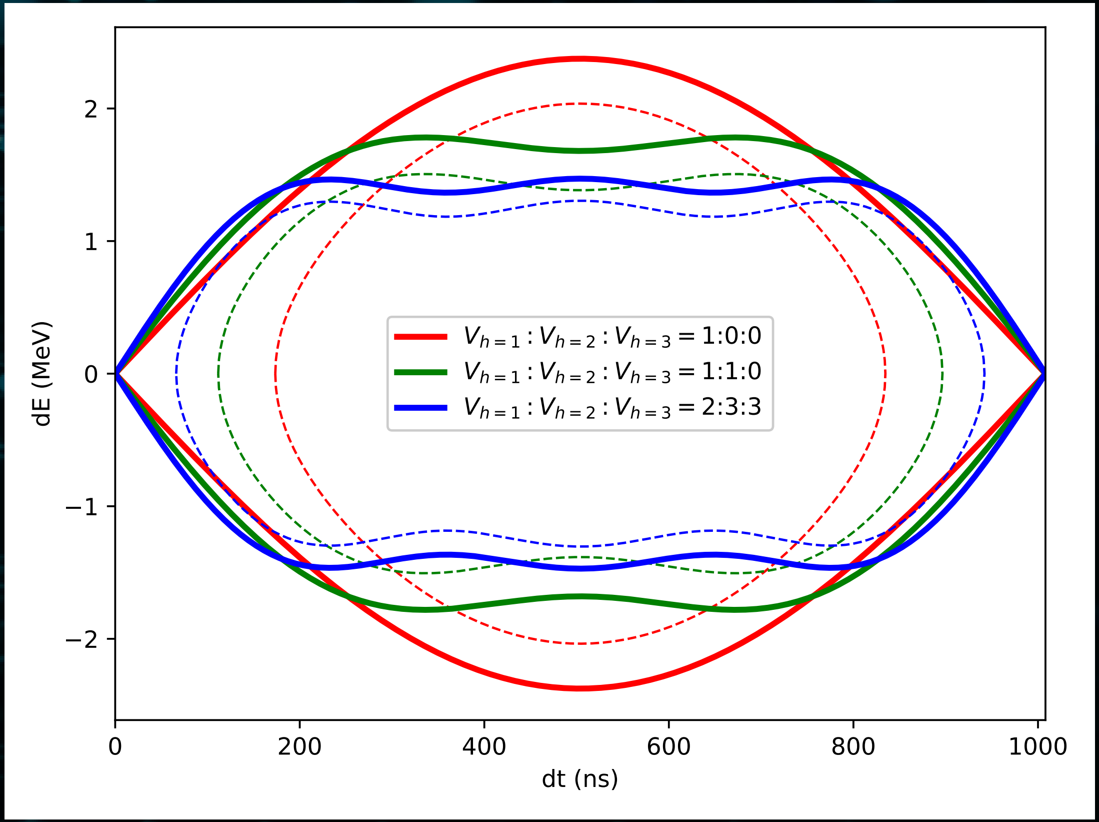


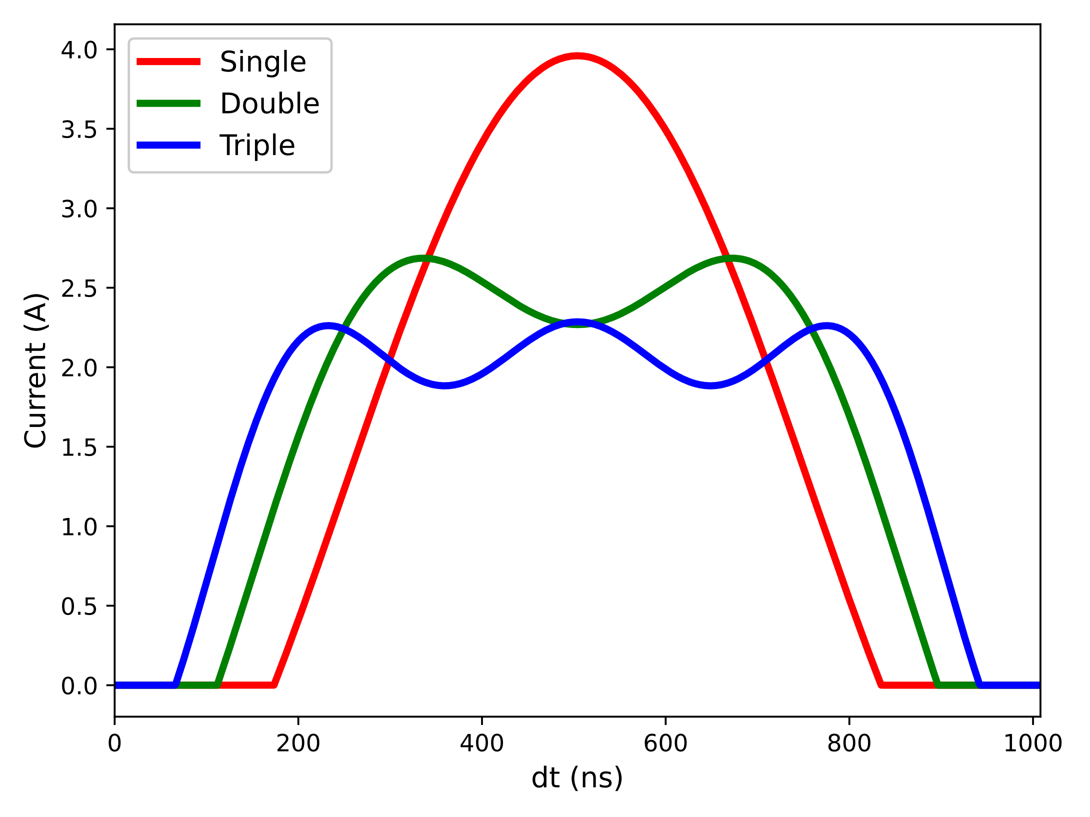
Triple Harmonic Capture

- Bunch lengthening with the 2nd RF harmonic is commonly used
- By including the 3rd RF harmonic, the bunch becomes even longer



Triple Harmonic Capture

- Bunch lengthening with the 2nd RF harmonic is commonly used
- By including the 3rd RF harmonic, the bunch becomes even longer
- With the same total voltage, the line density can be significantly reduced



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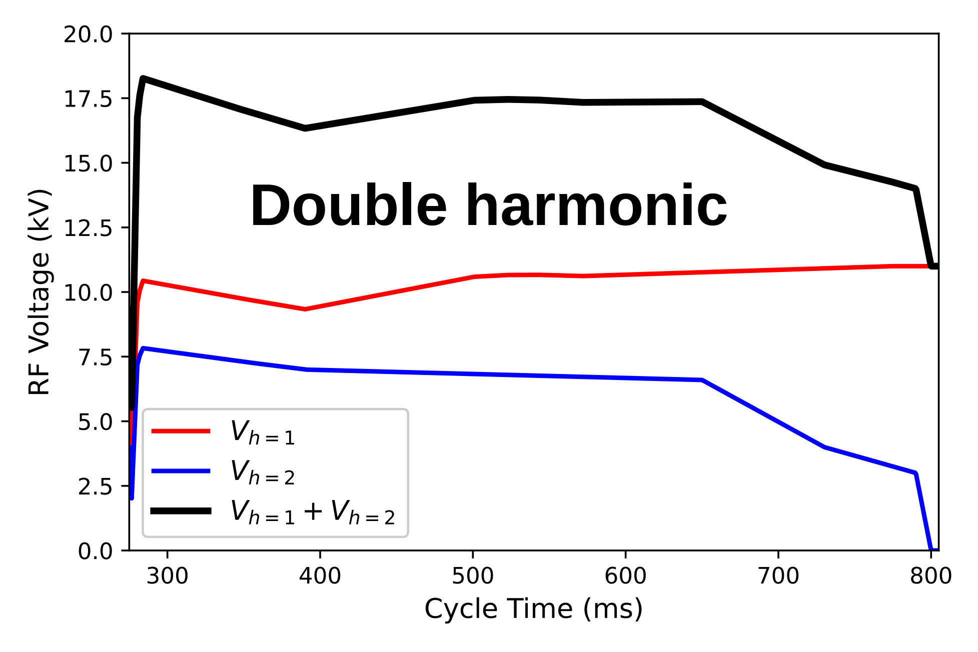
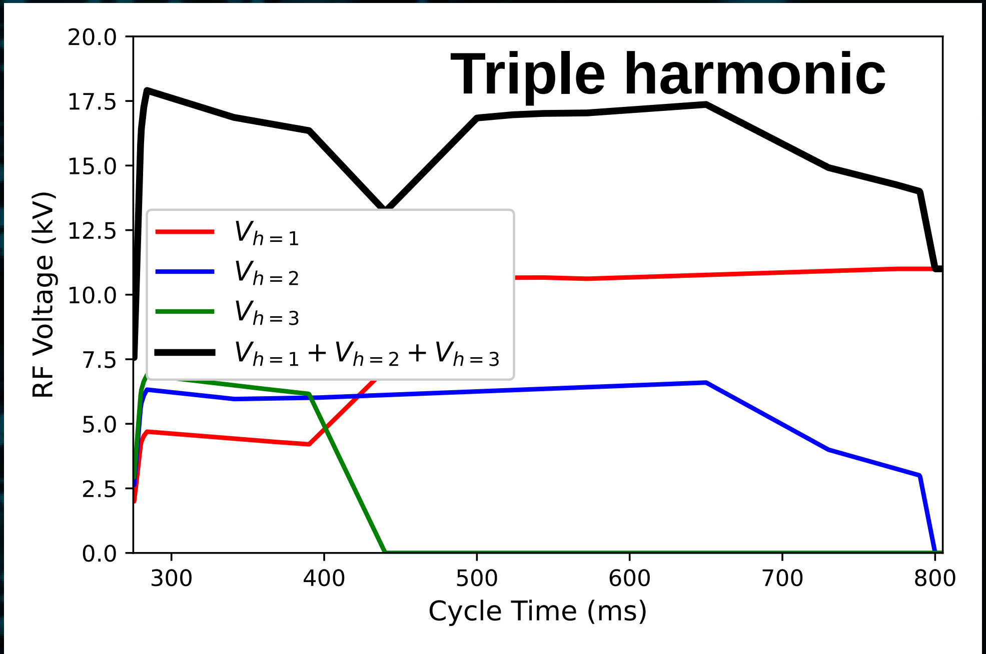
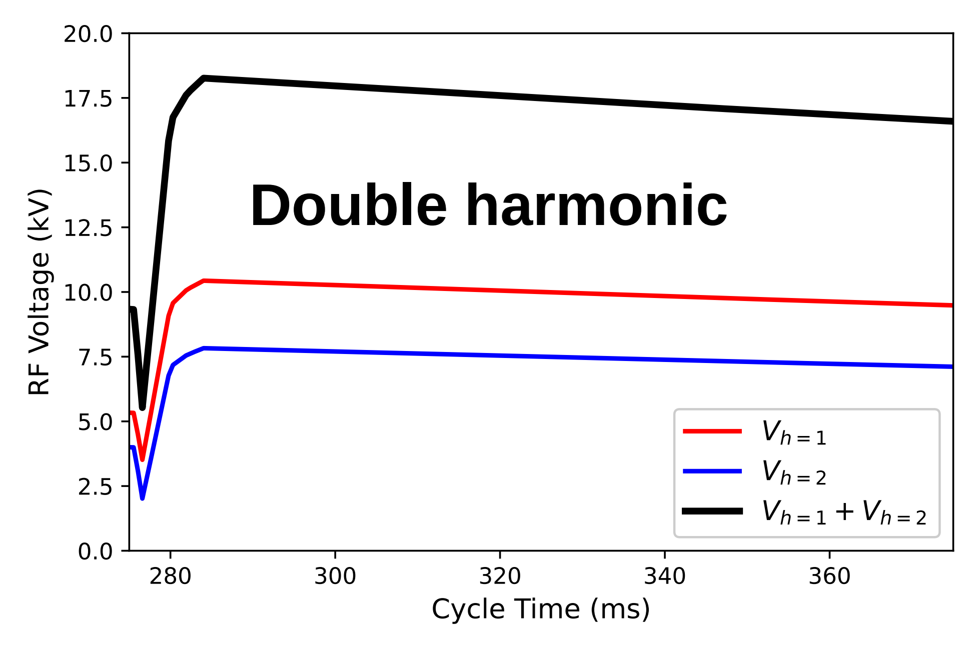
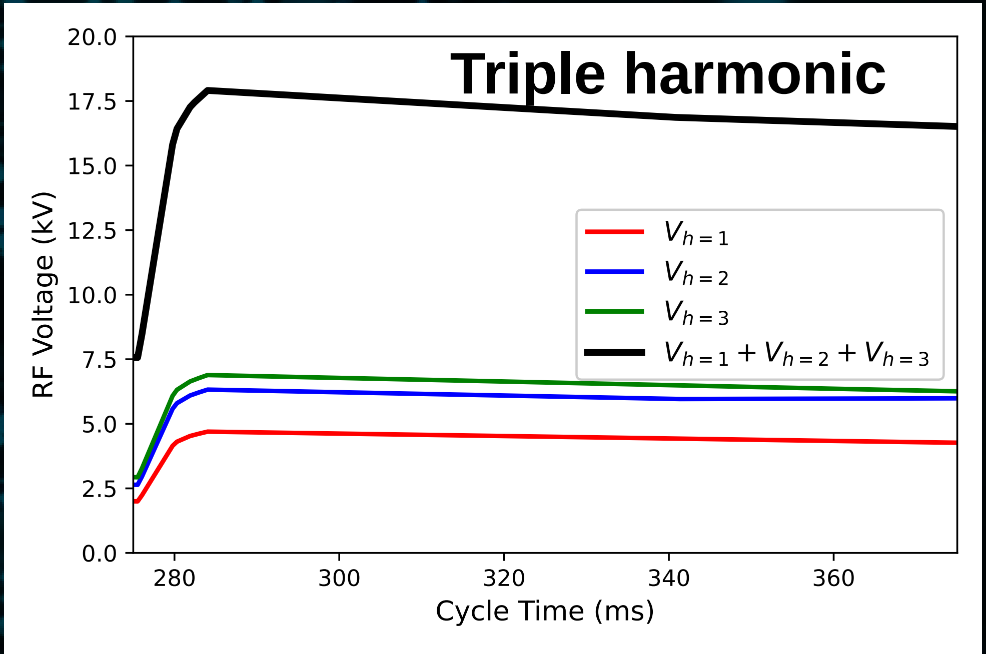




- Triple harmonic applied during the first 120 ms of the ramp in tests

Triple Harmonic Capture





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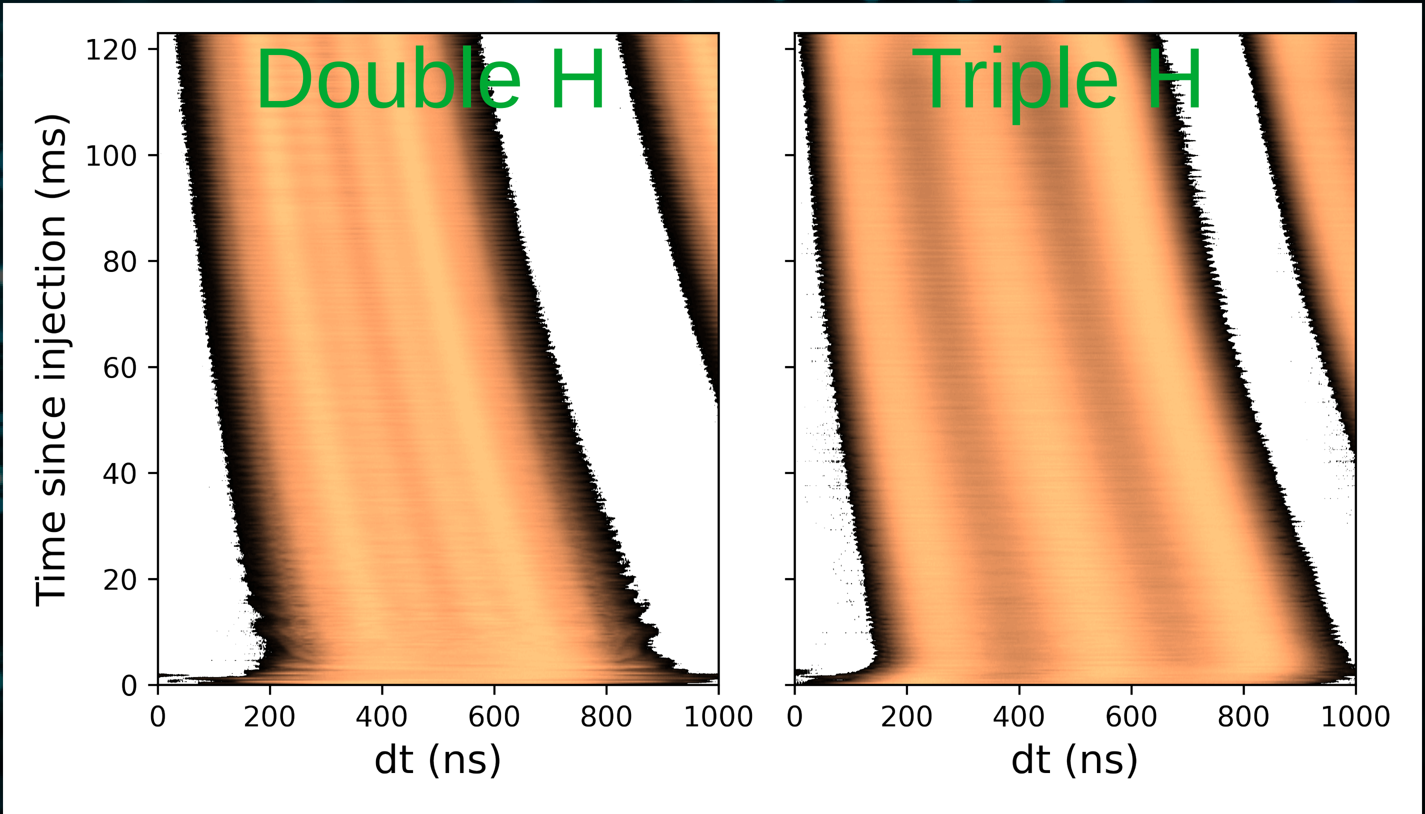
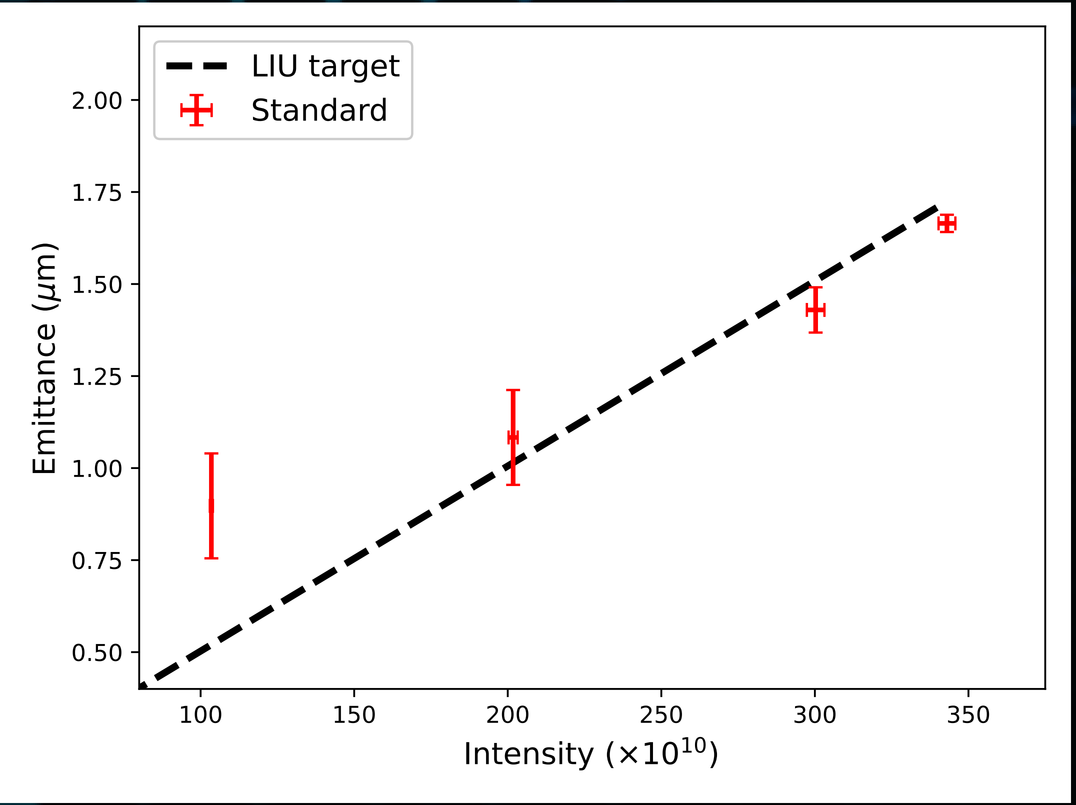


- Triple harmonic applied during the first 120 ms of the ramp in tests
- Clear increase in bunch length compared to double harmonic

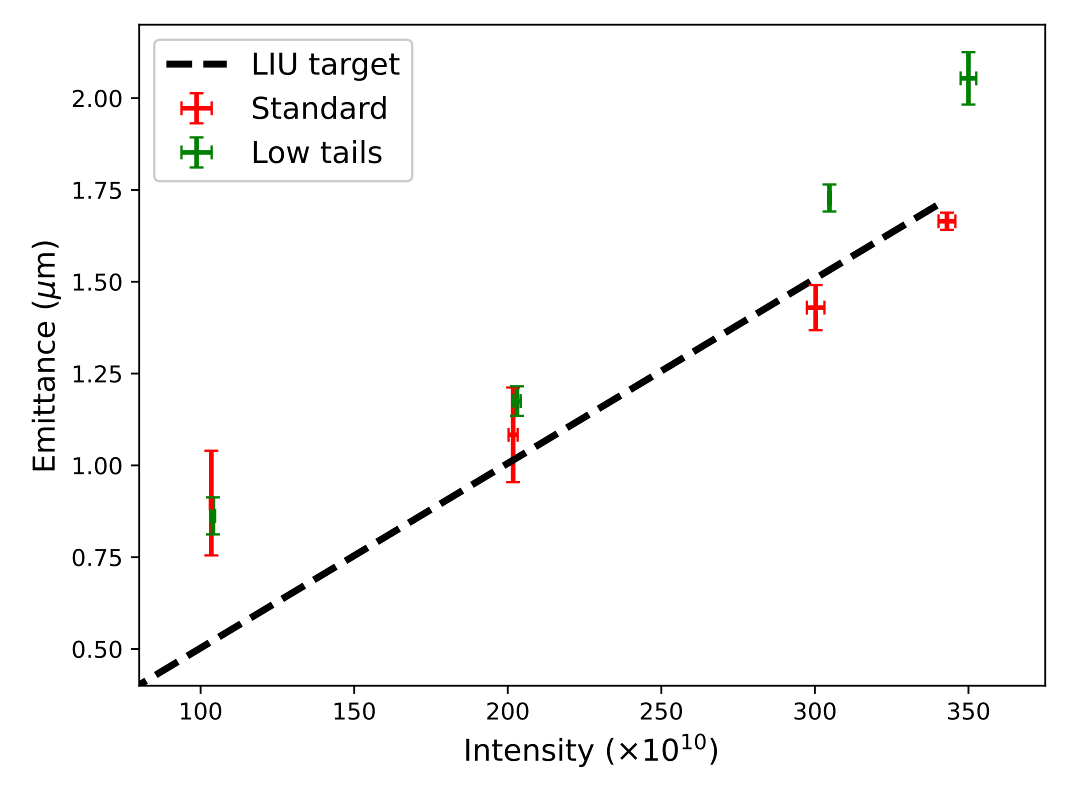
Brightness Preservation

- For LHC physics beams, the design brightness can be achieved, but tail formation is a problem



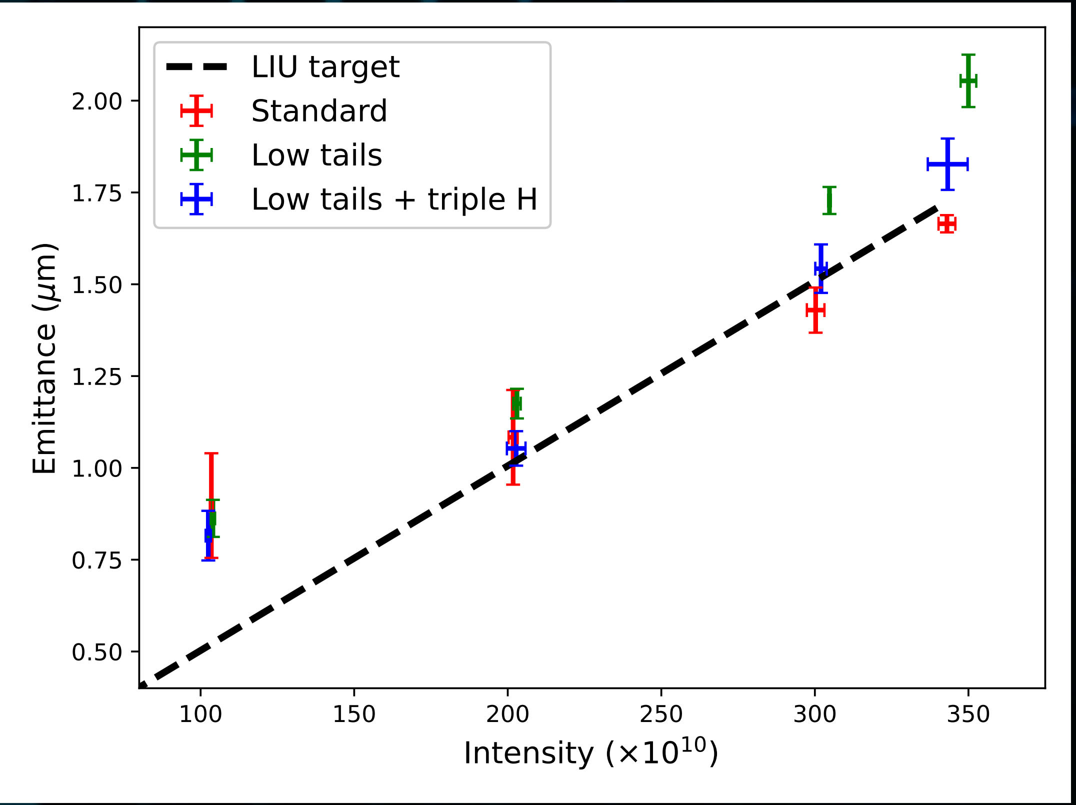
Brightness Preservation

- For LHC physics beams, the design brightness can be achieved, but tail formation is a problem
- After adapting the working point, both tails and brightness are reduced



Brightness Preservation

- For LHC physics beams, the design brightness can be achieved, but tail formation is a problem
- After adapting the working point, both tails and brightness are reduced
- Adding the third harmonic brings the brightness back to the target value



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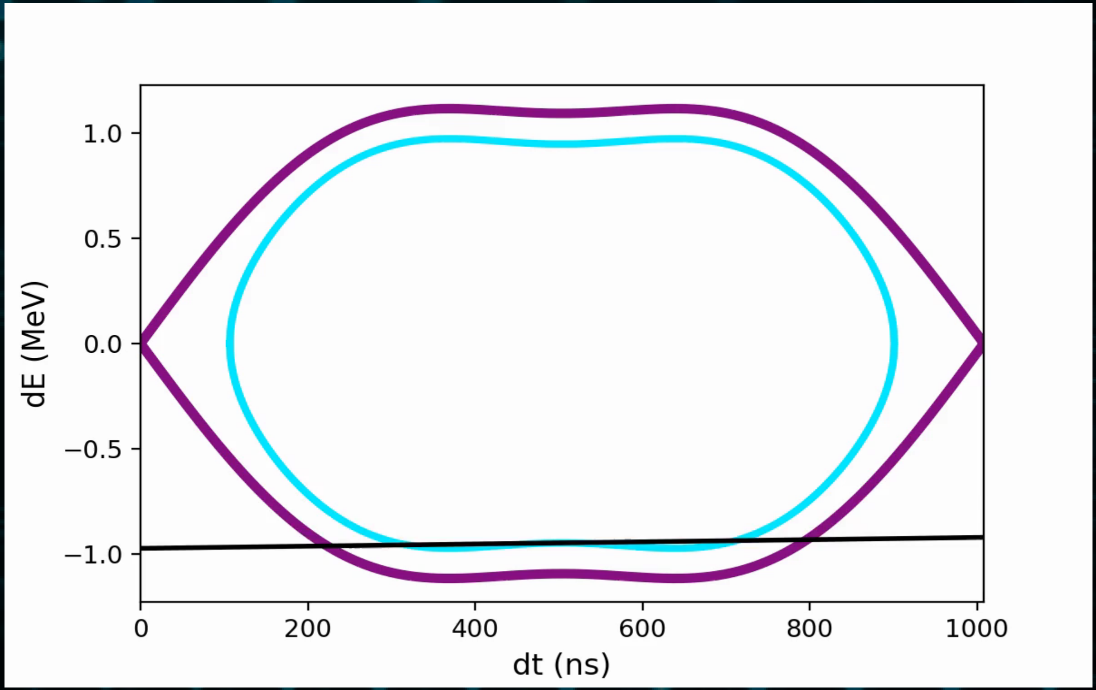
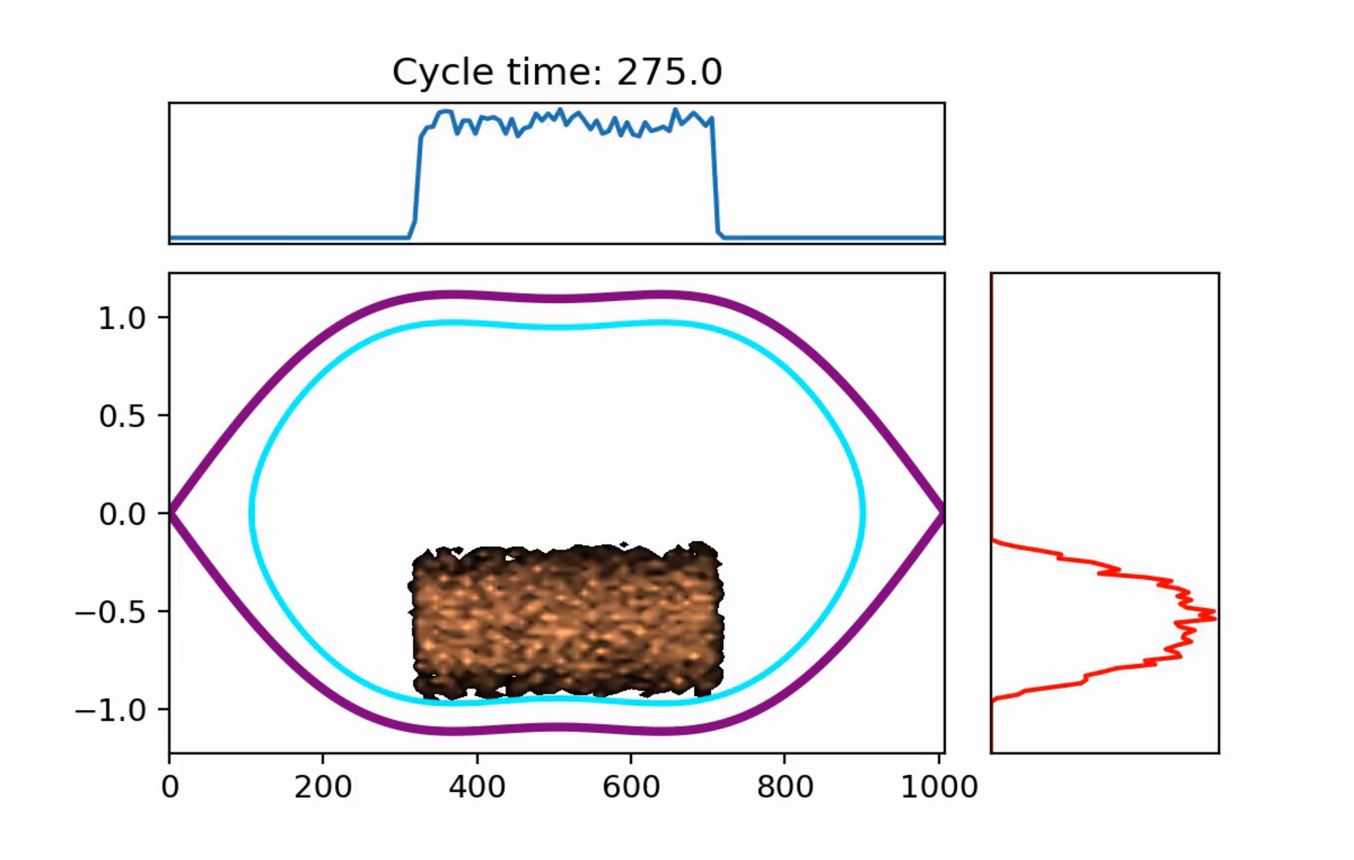
Longitudinal Painting

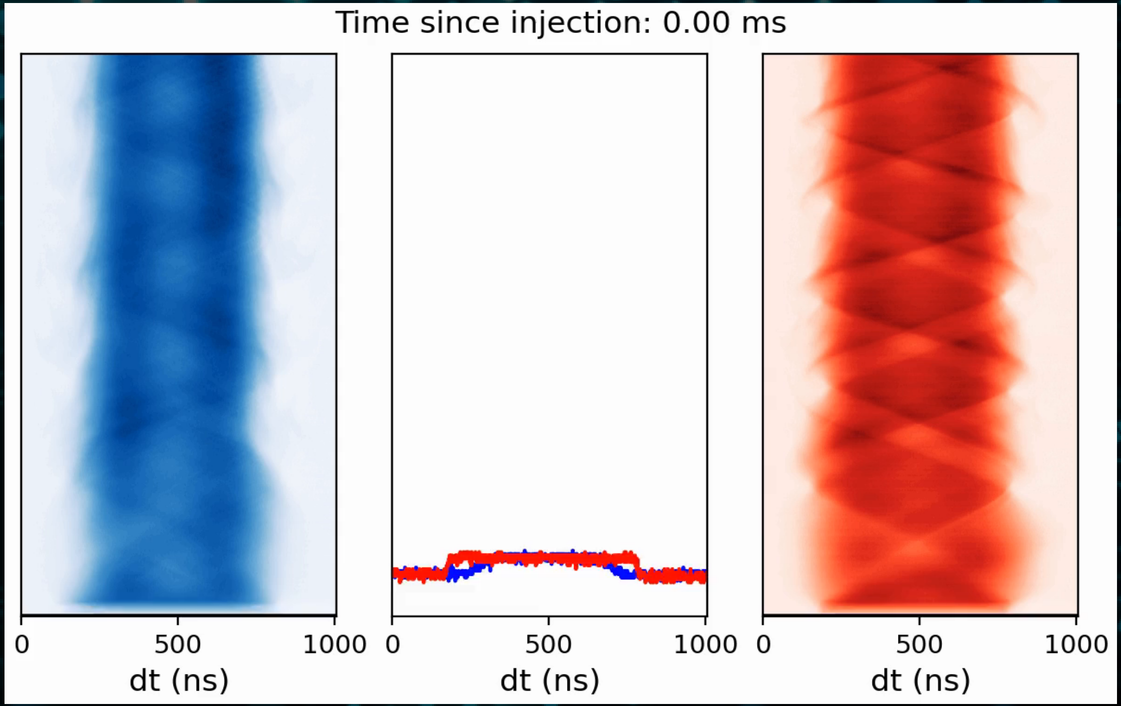


- Linac4 extraction energy can be modulated up to ±1.6 MeV
- The chopping is modulated at the same time to match the target contour
- The objective is to modulate the injected energy and bunch length to cover phase space uniformly

Longitudinal Painting



Implementation



Painted injection

Standard injection

- High intensity (~9x10^{12})
- Longitudinal emittance is approximately the same in both cases
- More oscillations in the standard case than the painted case
- Extracted transverse emittances $(\varepsilon_V+\varepsilon_H)/2$:

  Standard: ~10 μm
  Painted: ~8.7 μm

Contents

Conclusion

- Minimizing space charge at the start of the PSB cycle is essential for optimising beam production
- Flexible hardware allows a large parameter space for what is injected and how it is captured/accelerated
- Reinforcement learning shows promise to balance the competing objectives of increasing emittance and reducing filamentation in the longitudinal plane
- Triple harmonic operation has been demonstrated as a viable tool to further decrease the line density and therefore reduce transverse blow-up
- Longitudinal painting allows an (almost) matched distribution from injection, which will hopefully enable the maximum possible performance

Summary slide, 5th ICFA mini-workshop on Space Charge

Theme: Bridging the gap in space charge dynamics

In 1-2 sentences, summarize the content of this presentation
(If relevant, specify type of facility, species, tune shift):

Discussion of optimizations that can be made in the longitudinal plane to reduce space charge effects in the transverse plane. The focus is on protons at a few hundred MeV.

From your perspective, where is the gap regarding space charge effects? (understanding/control/mitigation/prediction/?)

The relationship between transient effects (line density fluctuations proportional to Q_s) and long term effects (average line density).

What is needed to bridge this gap?

Further study