PS Booster Longitudinal Beam Dynamics in Run 3:
New Challenges, New Possibilities

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Acknowledgements:
BLonD Developers, OP-PSB,
LIU-PSB, RF Colleagues past and present

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- Controlled longitudinal emittance blow-up
- Longitudinal instability
- Operational beam production
- Injection on the ramp
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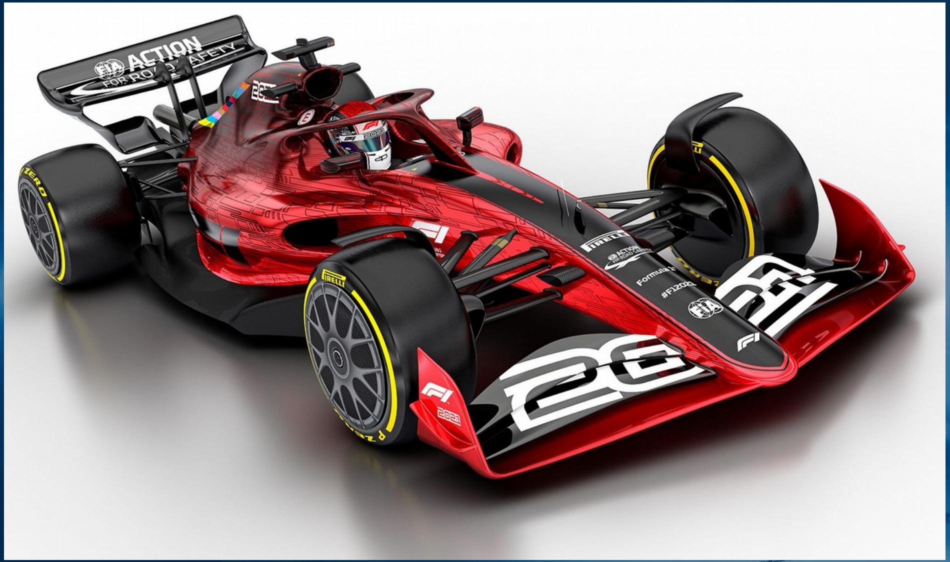
Introduction

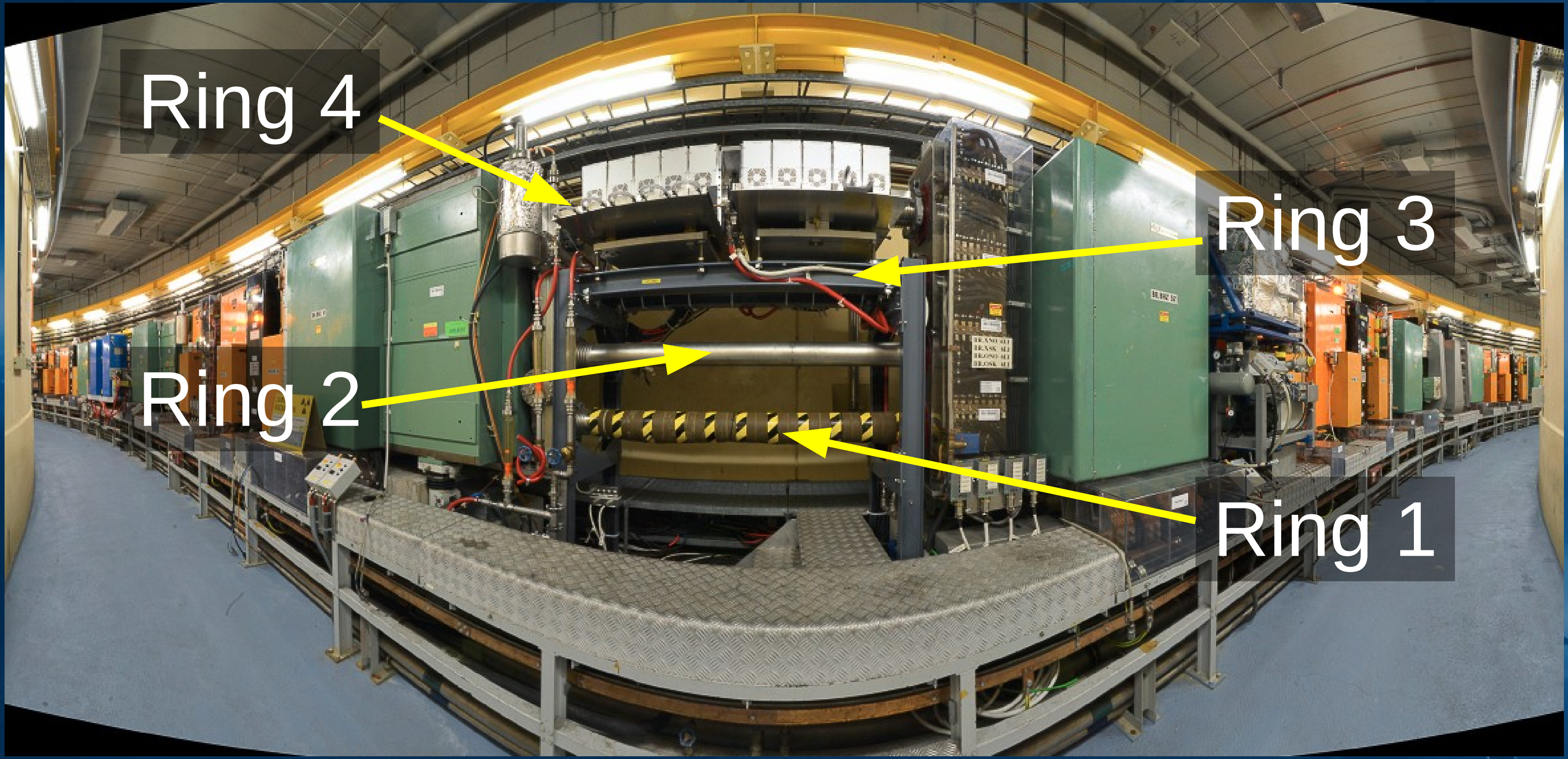
Introduction



LHC:
- High precision
- Single purpose

PSB:
- Rugged
- Multi purpose

Introduction



A Little History

- The PSB was designed as an intensity booster for the PS
- Fine precision was less of a priority than delivering high intensity beams and increasing PS injection energy
- Since then, increased precision and control has been required, especially in the LHC era
- To meet the needs of the HL-LHC, significant upgrades were required

Changes During LS2

Most significant changes from the longitudinal perspective:

- Finemet RF cavities:

  More flexibility thanks to large bandwidth, but also stronger interactions with the beam, feedback loops help to suppress the interaction

- Linac4:

  Higher injection energy and bunch-to-bucket injection, longitudinal painting in the long term

- POPS-B:

  Higher extraction energy and increased ramp rate

Introduction

Before and After

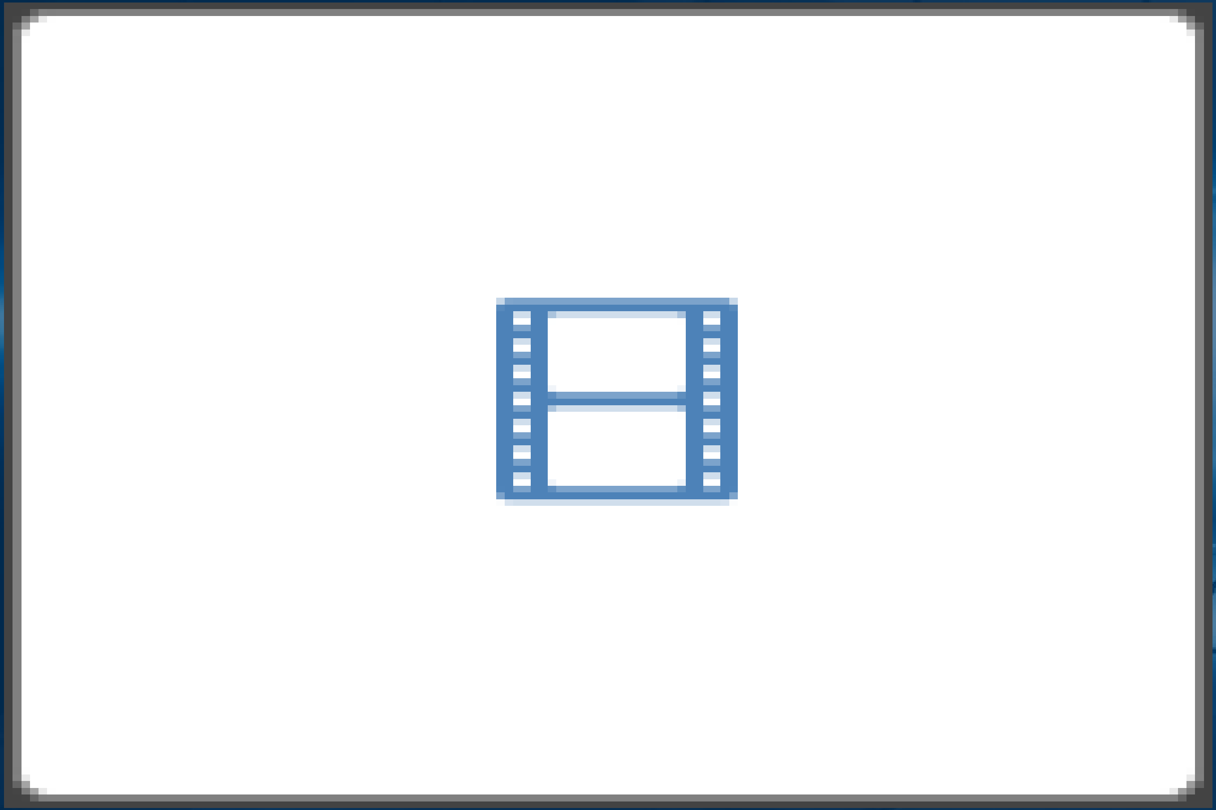
Controlled Longitudinal Emittance Blow-up

Controlled Longitudinal Emittance Blow-Up

- Controlled longitudinal emittance blow-up is needed for three main reasons:
  1) Provide controlled and reproducible longitudinal distribution
  2) Increase stability threshold in the PSB
  3) Reduce space charge effects on the PS flat bottom
- Pre-LS2, a dedicated high harmonic RF system was used with single tone modulation
- Post-LS2, band limited phase noise will be used for almost all operational beams
- Blow-up with phase noise is more easily optimised and requires fewer parameters to be controlled than single tone modulation of a high harmonic

Controlled Longitudinal Emittance Blow-Up

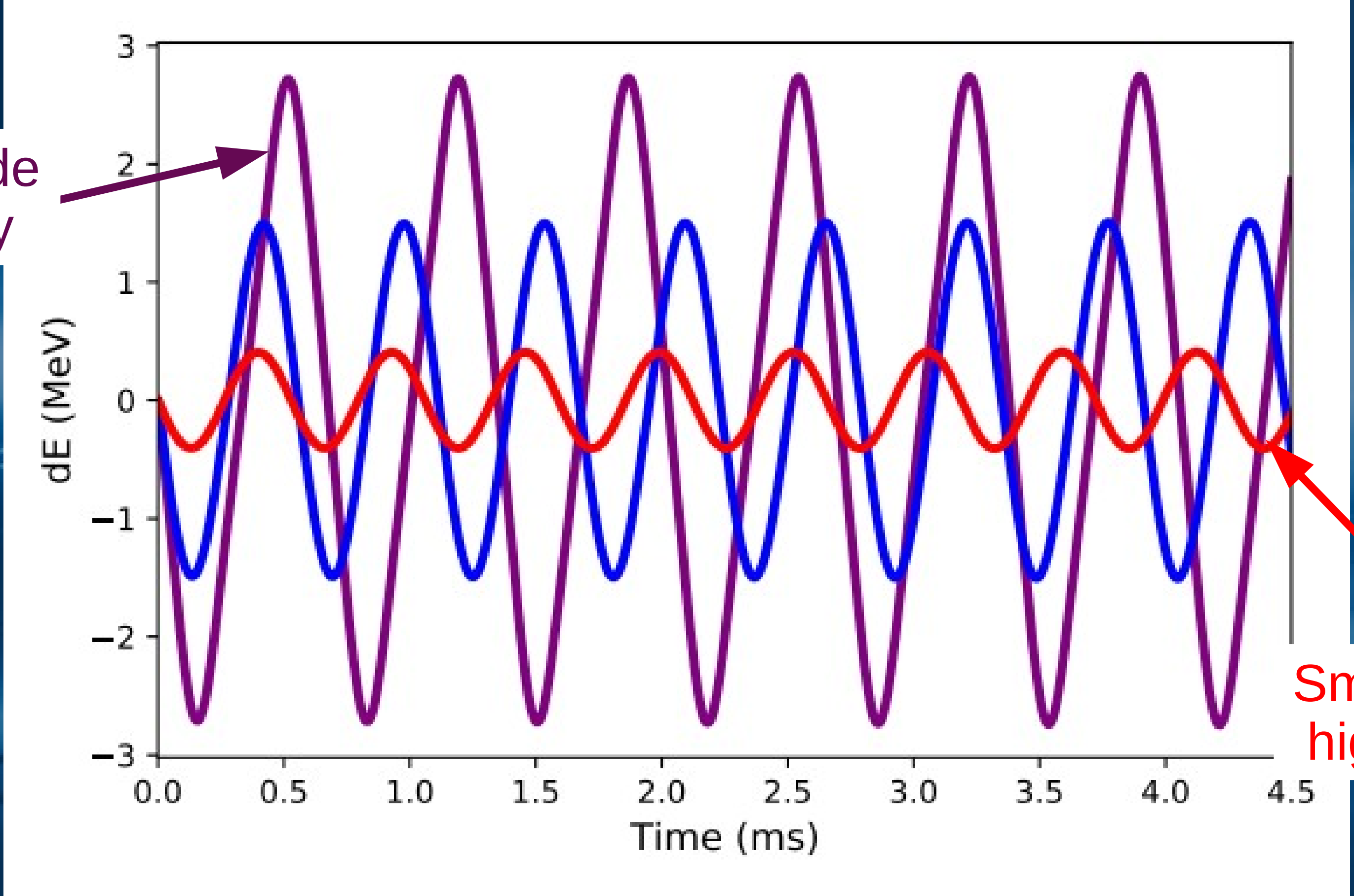
Synchrotron Motion



- Particles in the bucket undergo synchrotron oscillations
- The frequency of the oscillations is the synchrotron frequency
- Particles nearer the separatrix have a lower synchrotron frequency than particles nearer the center

Controlled Longitudinal Emittance Blow-Up

Synchrotron Motion



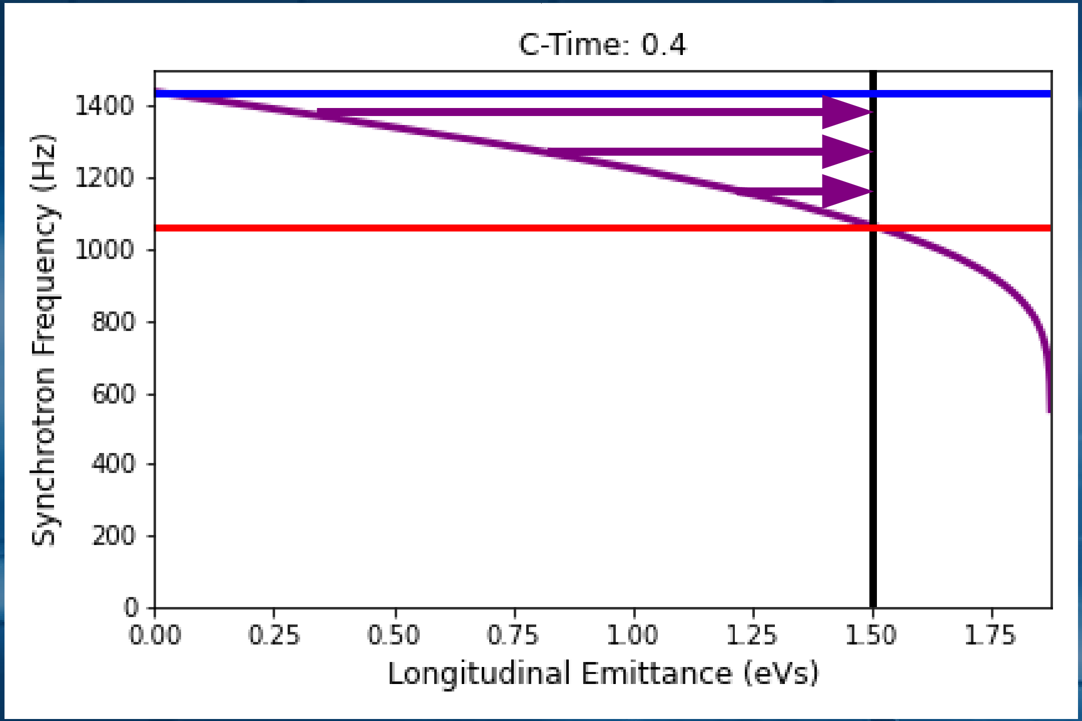
Large amplitude low frequency

Small amplitude high frequency

Controlled Longitudinal Emittance Blow-Up

Synchrotron Frequency Distribution

- The distribution of frequencies within the bucket can be calculated as a function of longitudinal emittance
- The RF phase should be modulated uniformly within the defined frequency range



Controlled Longitudinal Emittance Blow-Up

Noise Band

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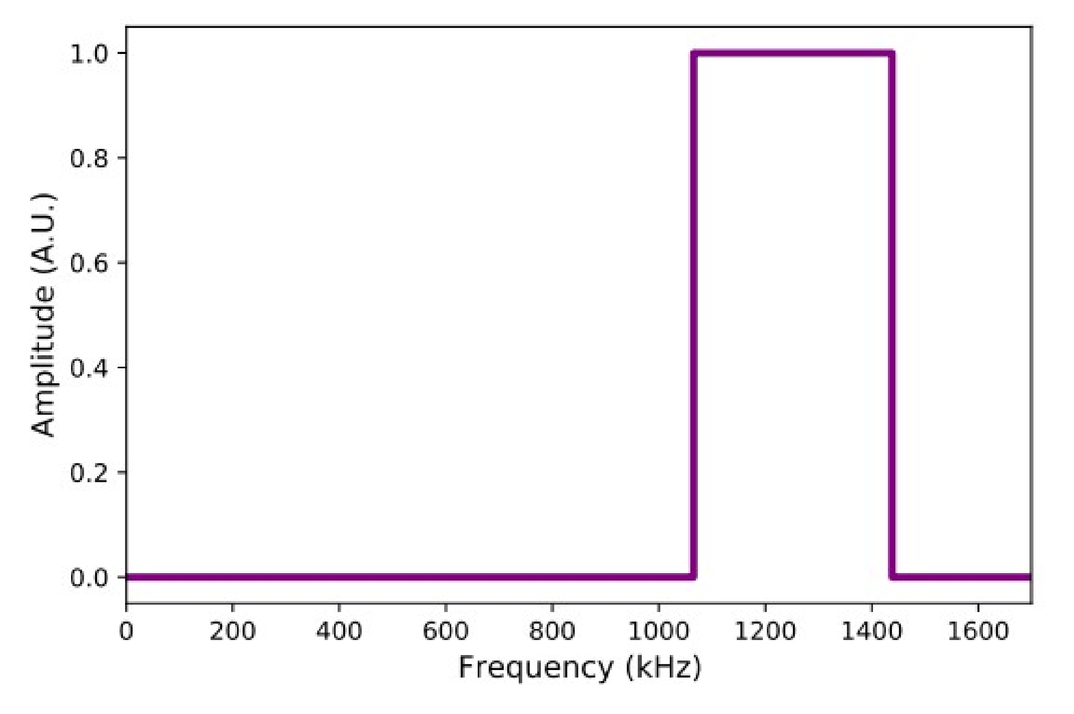
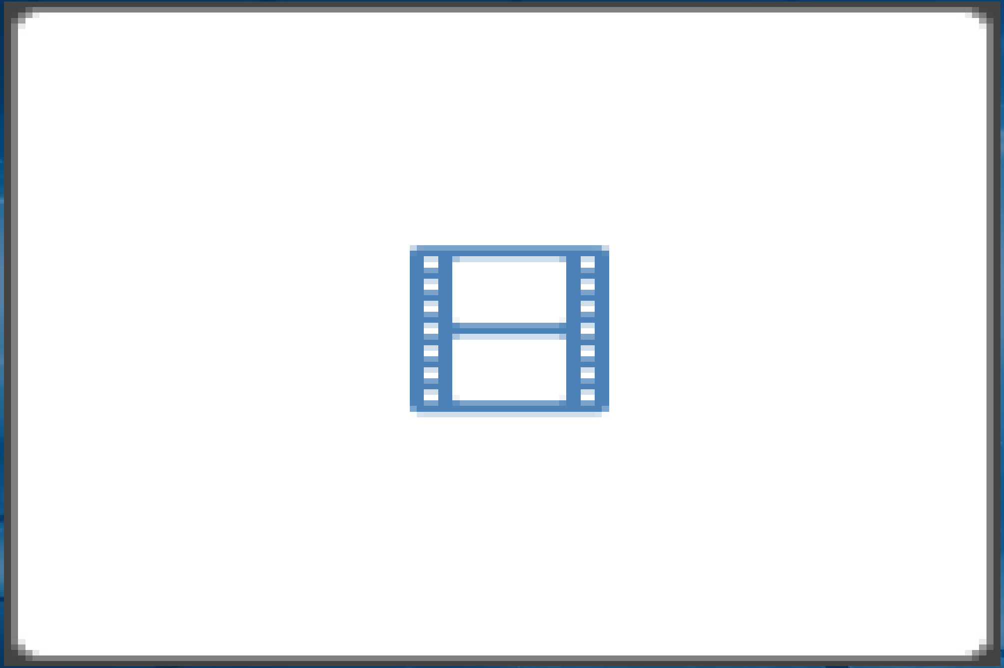


Time Variation of Noise Band

- During acceleration, the synchrotron frequency distribution changes a lot and very quickly
- The noise program needs to follow the changing distribution to excite the correct particles



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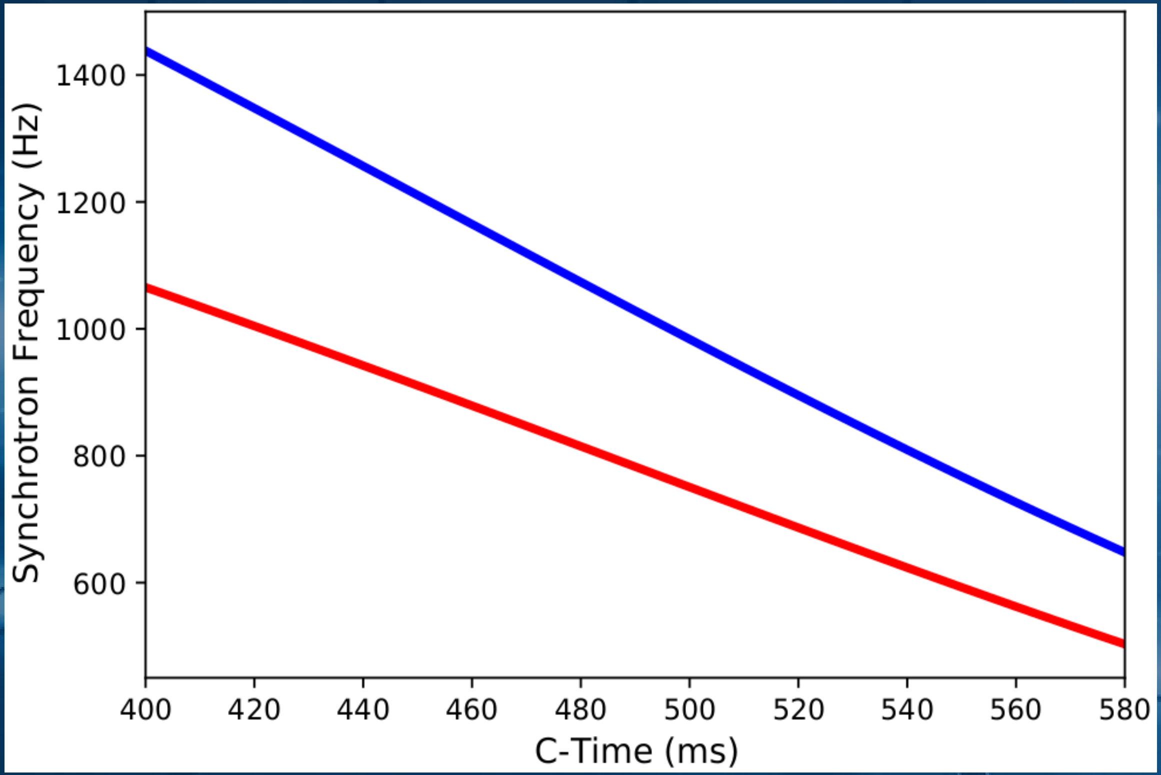
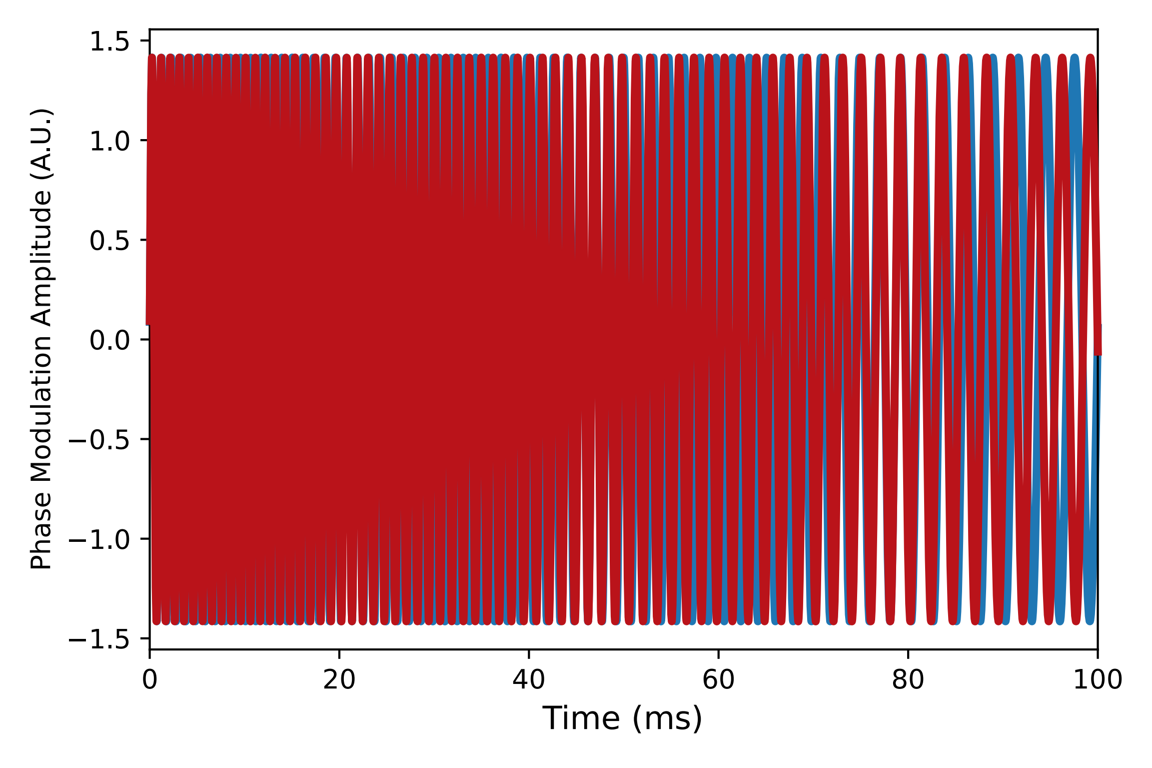


Controlled Longitudinal Emittance Blow-Up

Time Domain Variable Frequency Modulation

1000 Hz

1050 Hz



300 Hz

320 Hz

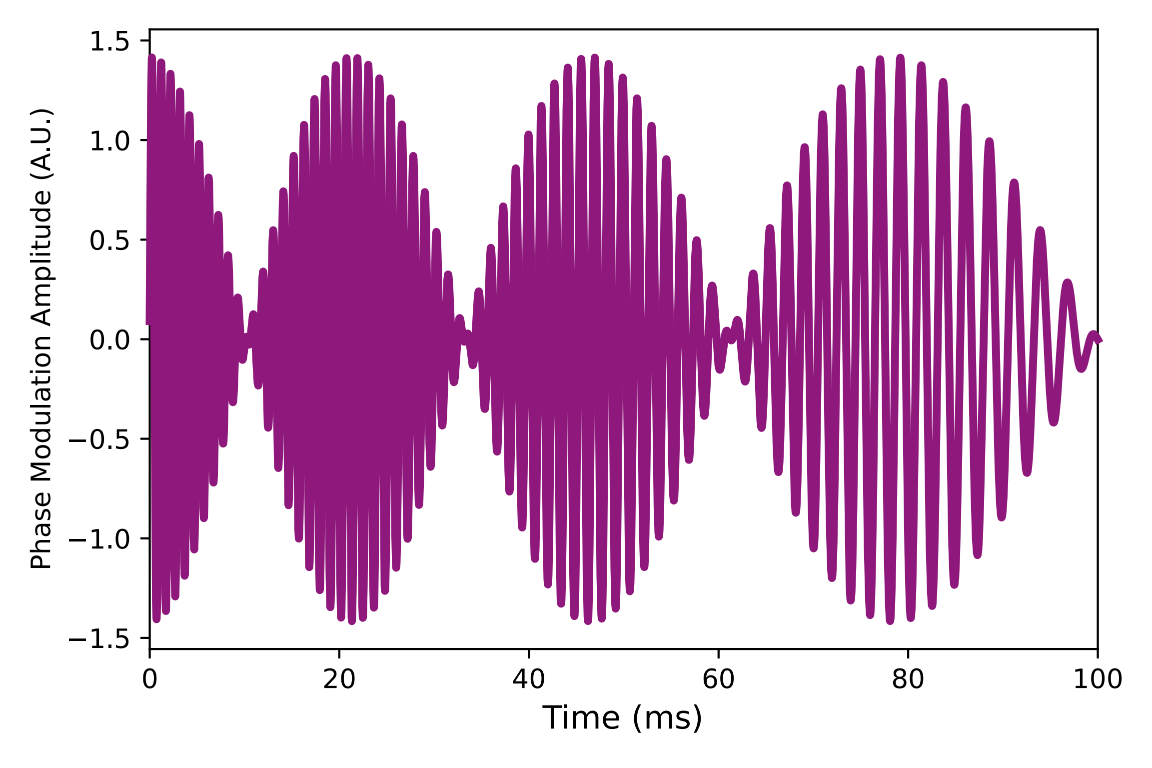
Controlled Longitudinal Emittance Blow-Up

Time Domain Variable Frequency Modulation

1000 Hz

+

1050 Hz



300 Hz

+

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Controlled Longitudinal Emittance Blow-Up

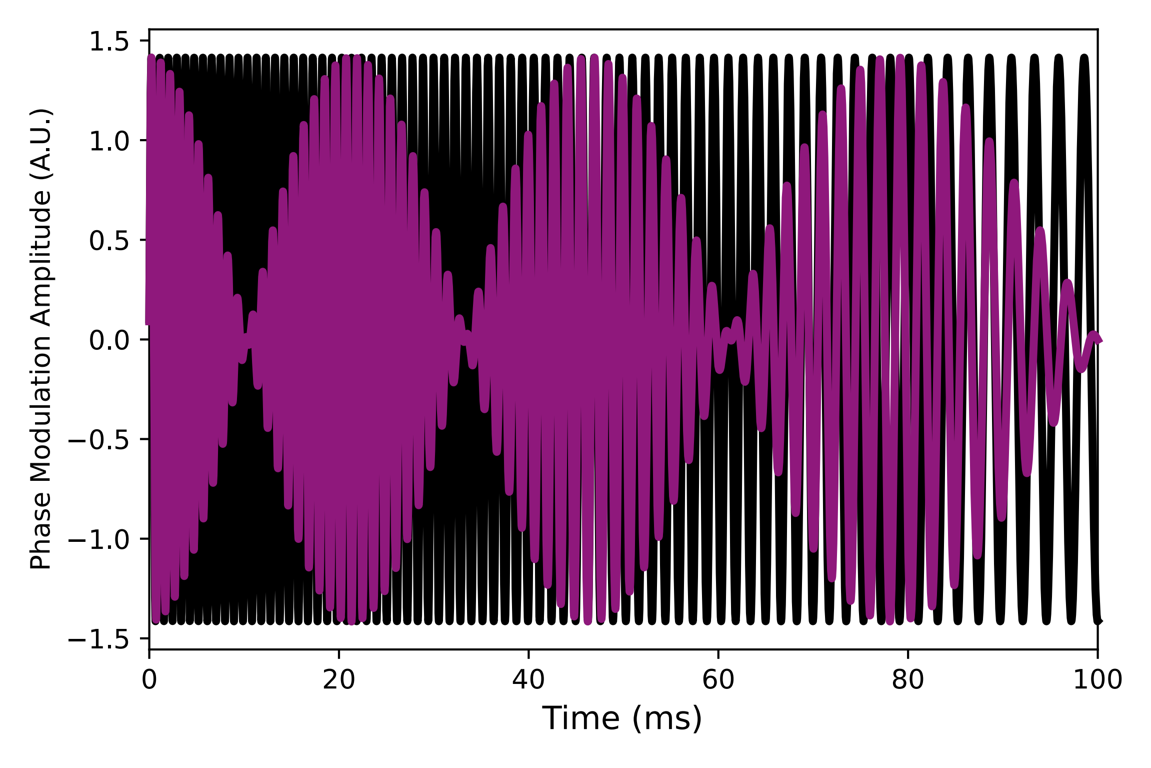
Time Domain Variable Frequency Modulation

1000 Hz

+

1050 Hz

1125 Hz



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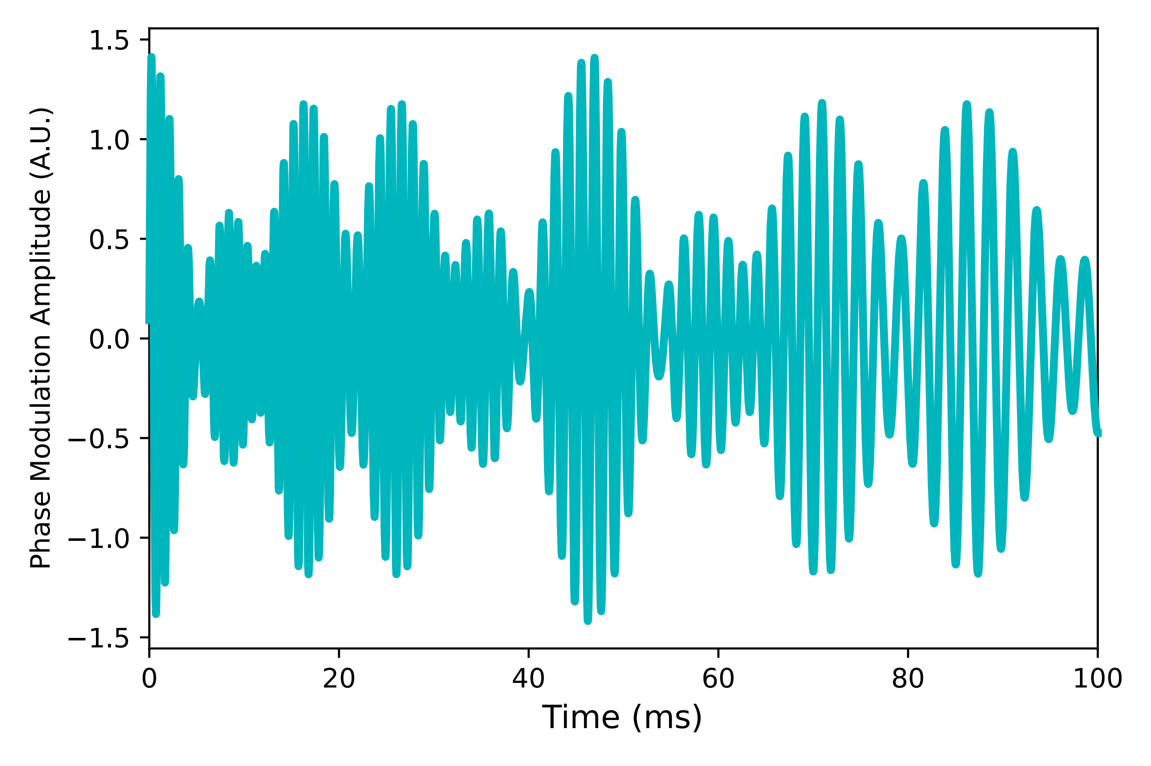

300 Hz

+

320 Hz

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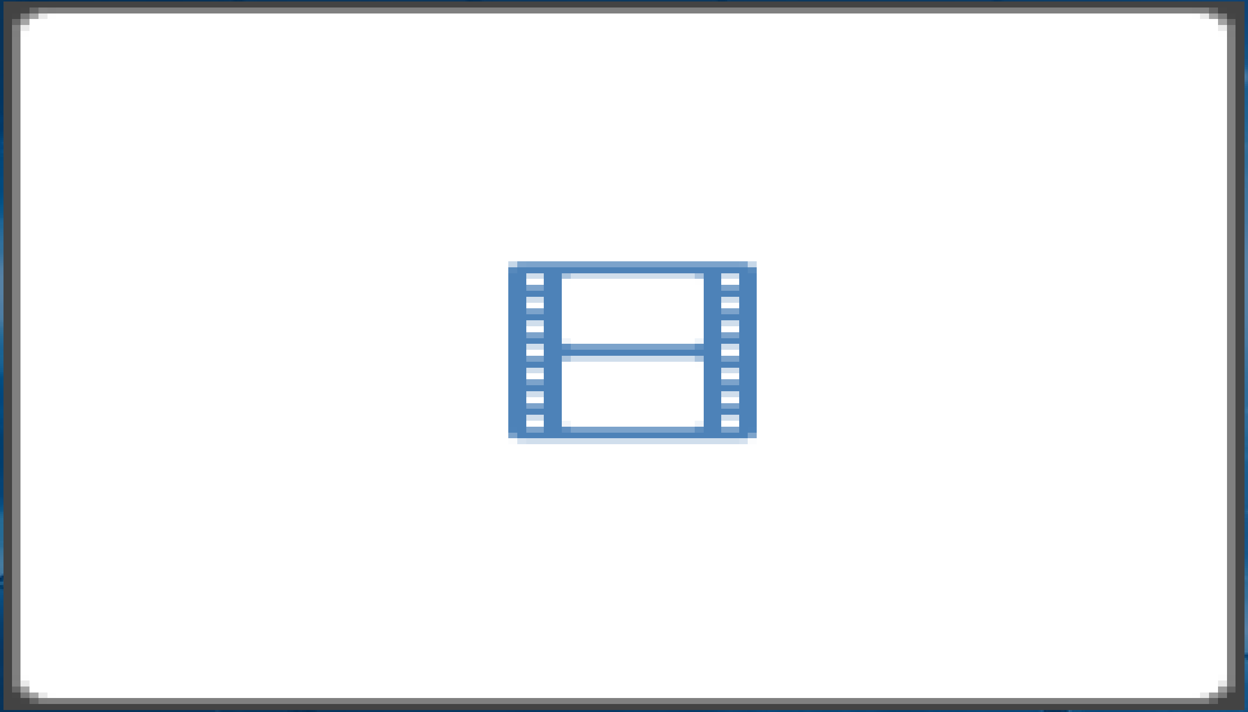
350 Hz

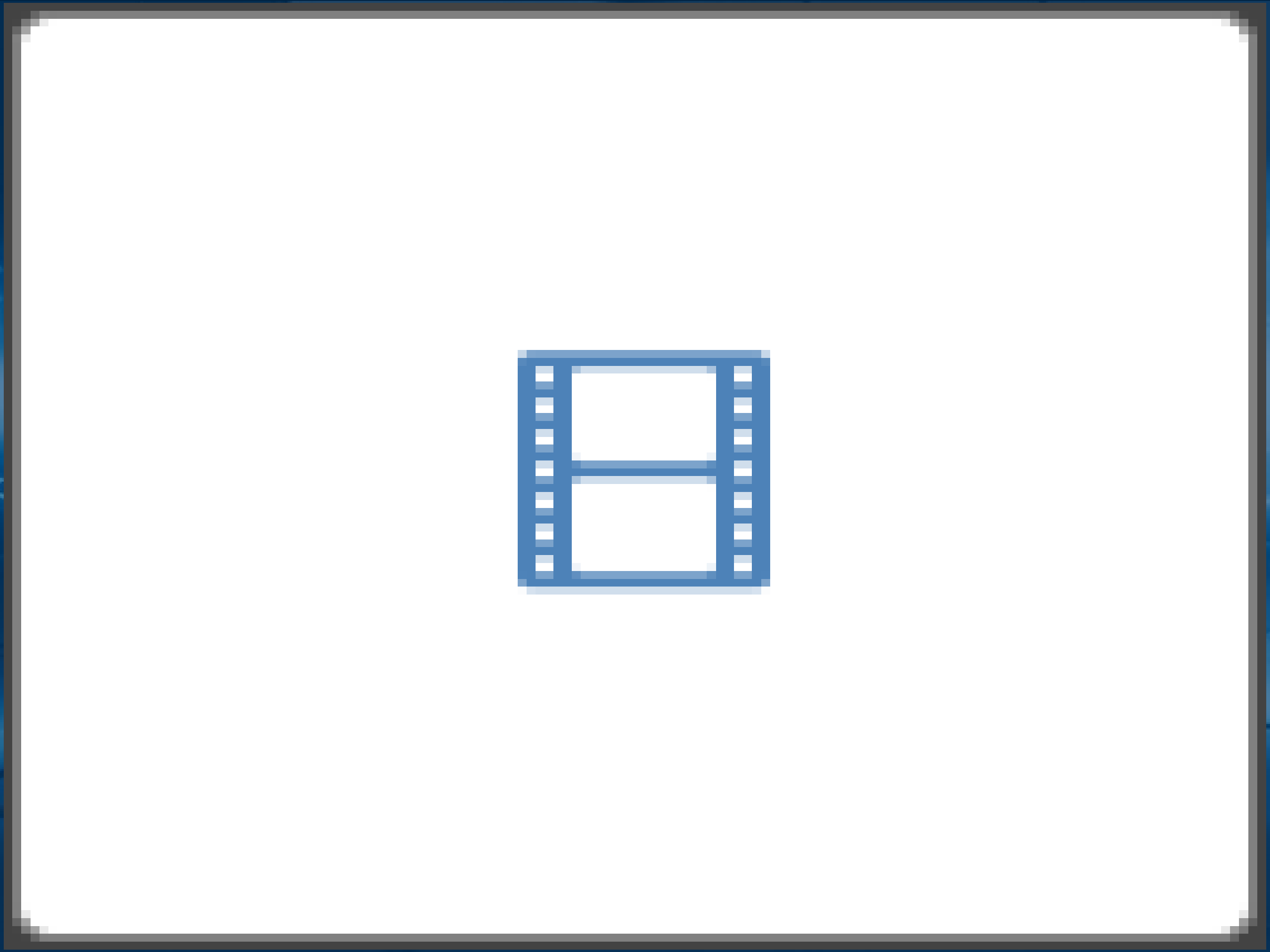
Smoothly Varying Noise Program

- Summing a very large number of waveforms creates a noise program
- As each contribution is smoothly varying, so is the final noise program



Controlled Longitudinal Emittance Blow-Up

Application of Phase Noise



Controlled Longitudinal Emittance Blow-Up

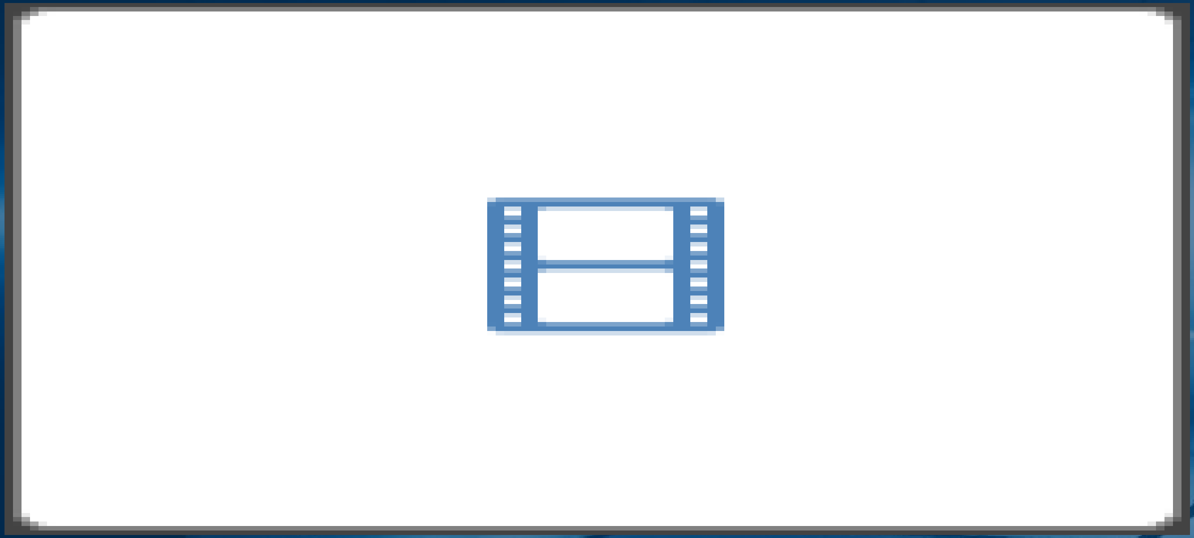
- Phase noise is used operationally in the SPS and LHC for controlled longitudinal emittance blow-up
- PSB phase noise proof-of-principle by D. Quartullo in 2017 (CERN-THESIS-2019-006)
- A new method of calculating noise was developed for the 2018 reliability run in the PSB
- All operational beams, with the exception of LHC single bunch beams, will use phase noise post-LS2

Longitudinal Instability

COURTESY BOB DAEMMRICH

Longitudinal Instability

Wakefield

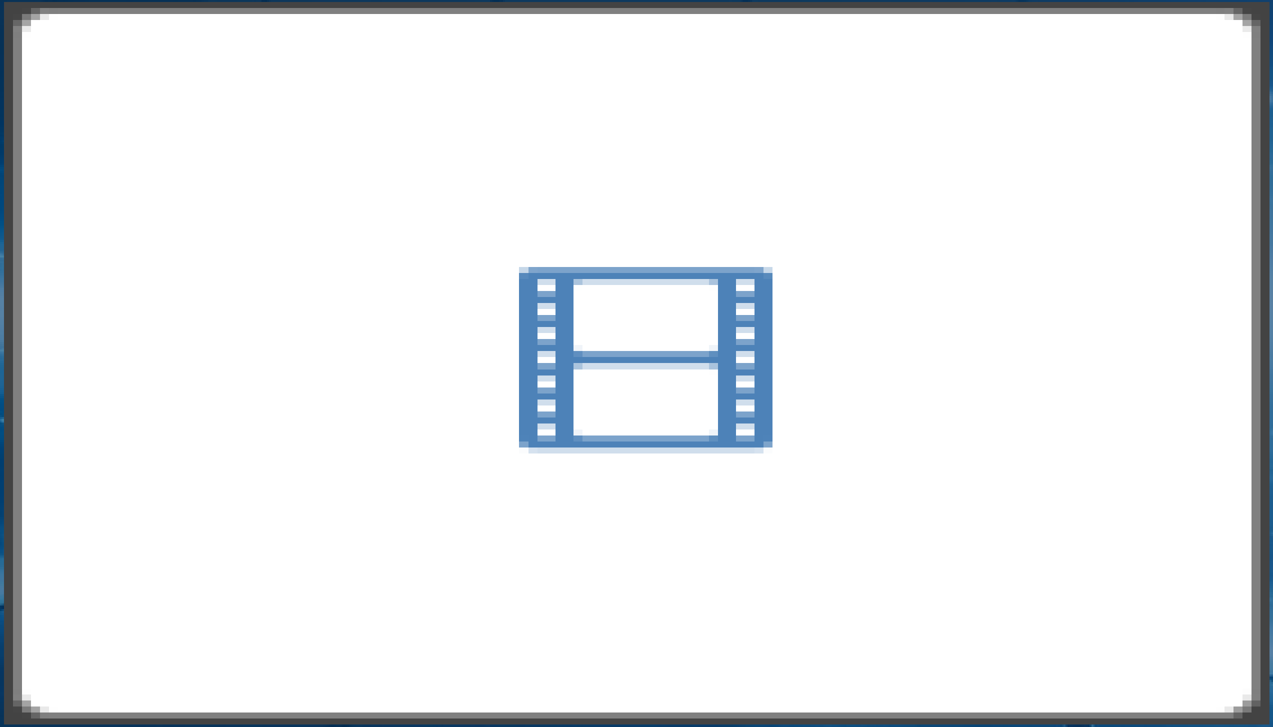


- Simulation by A. Farricker of the impedance of the new extraction kicker
- As protons pass through a trailing field is left behind, which will be seen by others
- Interactions between protons and the environment can lead to instability

Longitudinal Instability

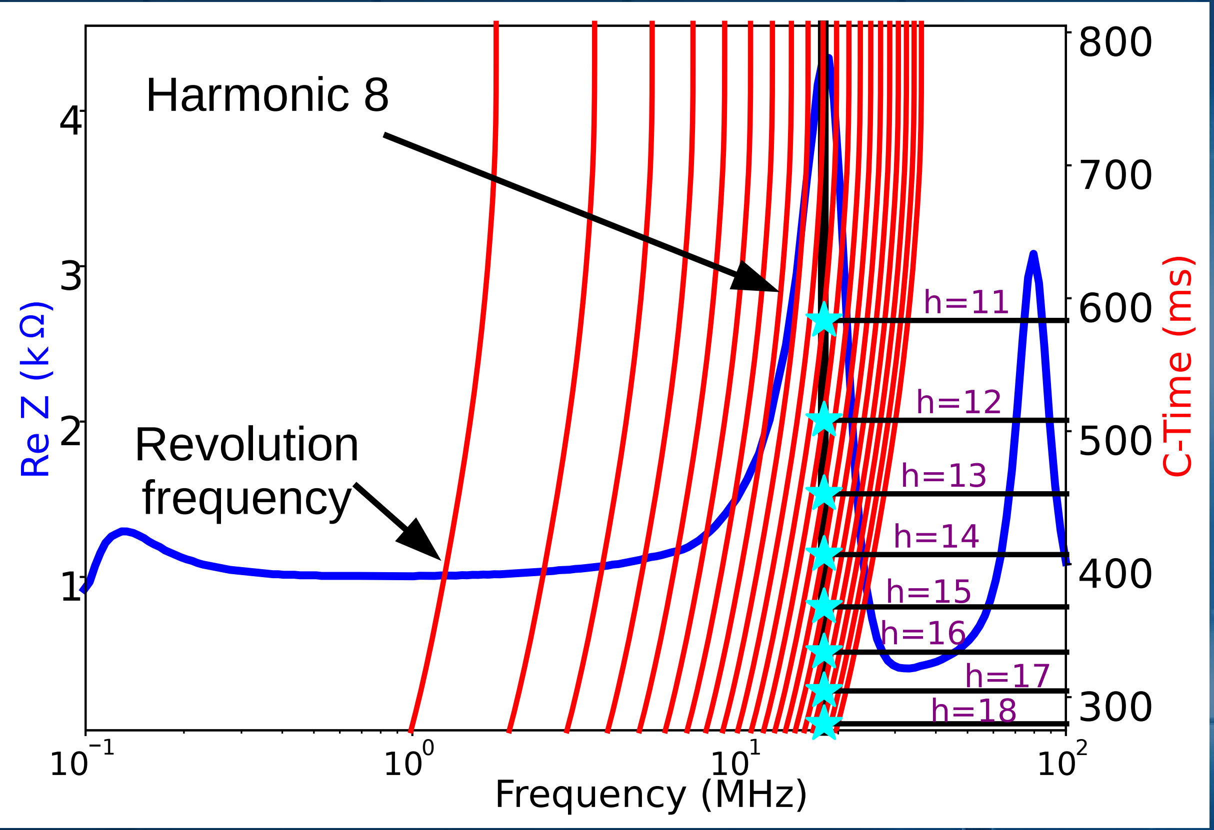
Impedance Model

- From injection to extraction, the revolution frequency changes by about a factor of 2
- With the changing revolution frequency the impedance also changes

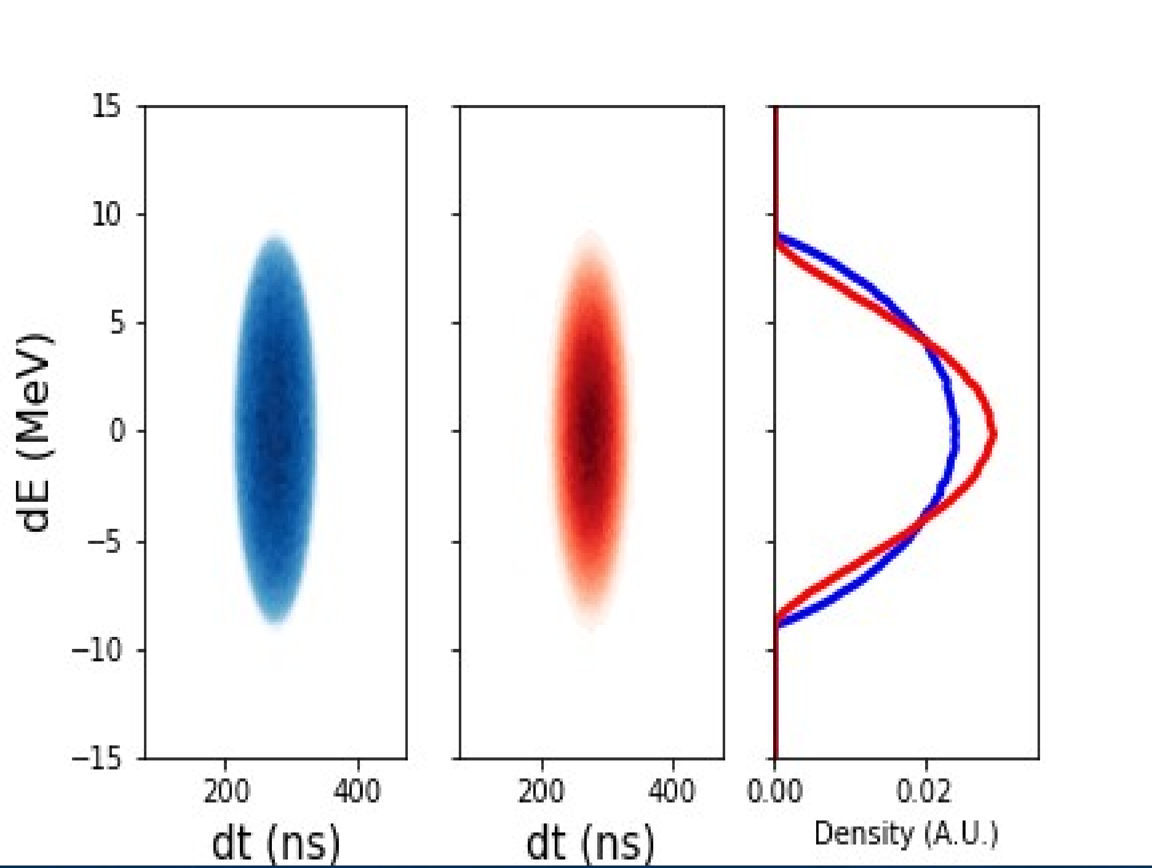


Finemet Impedance

- Finemet cavities are the dominant impedance source and are able to trigger microwave instability
- Due to the changing β during acceleration, different revolution harmonics sweep through the large impedance peak during the cycle



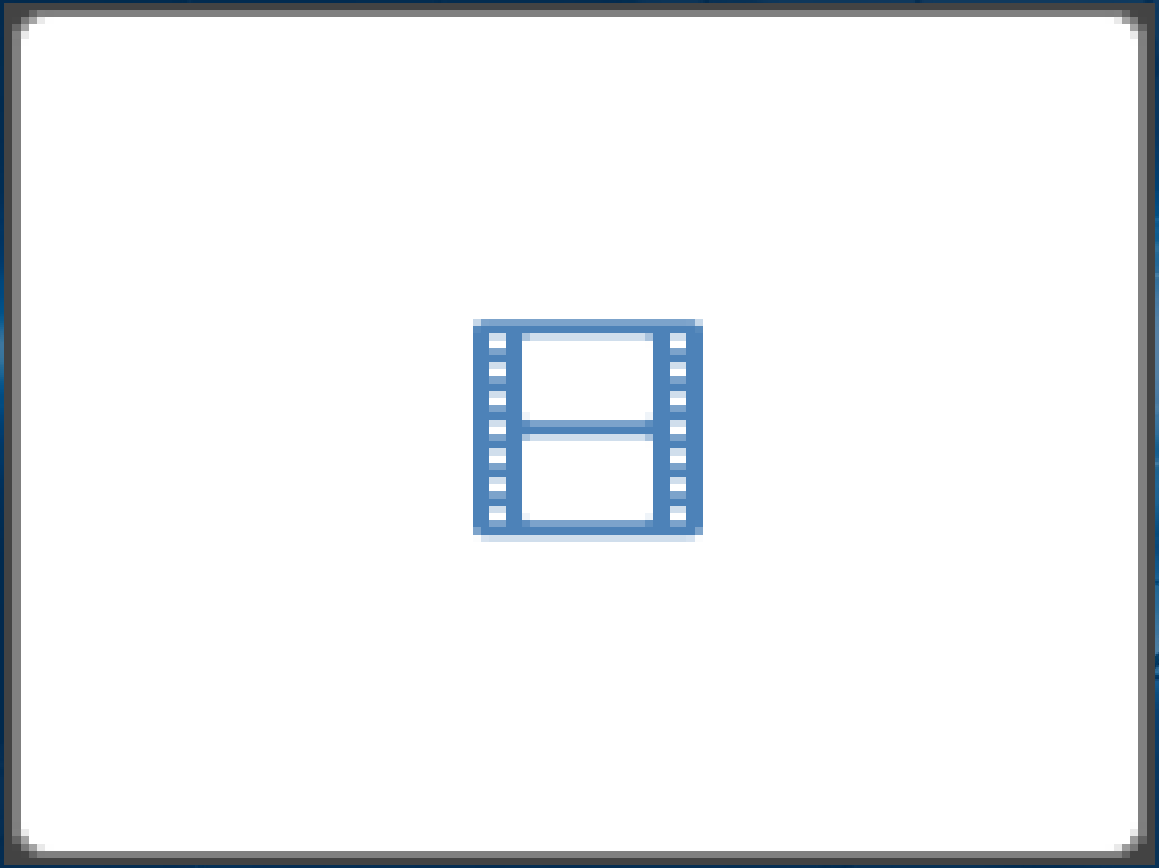
Bunch Distribution



- Two almost identical bunches at flat top, only the longitudinal distribution is different
- Binomial distribution with μ = 0.3 (blue) and μ = 1 (red)

$$\lambda(x) = \left[1 - \left(2\frac{x}{\tau}\right)^2\right]^{\mu+\frac{1}{2}}$$

Bunch Distribution



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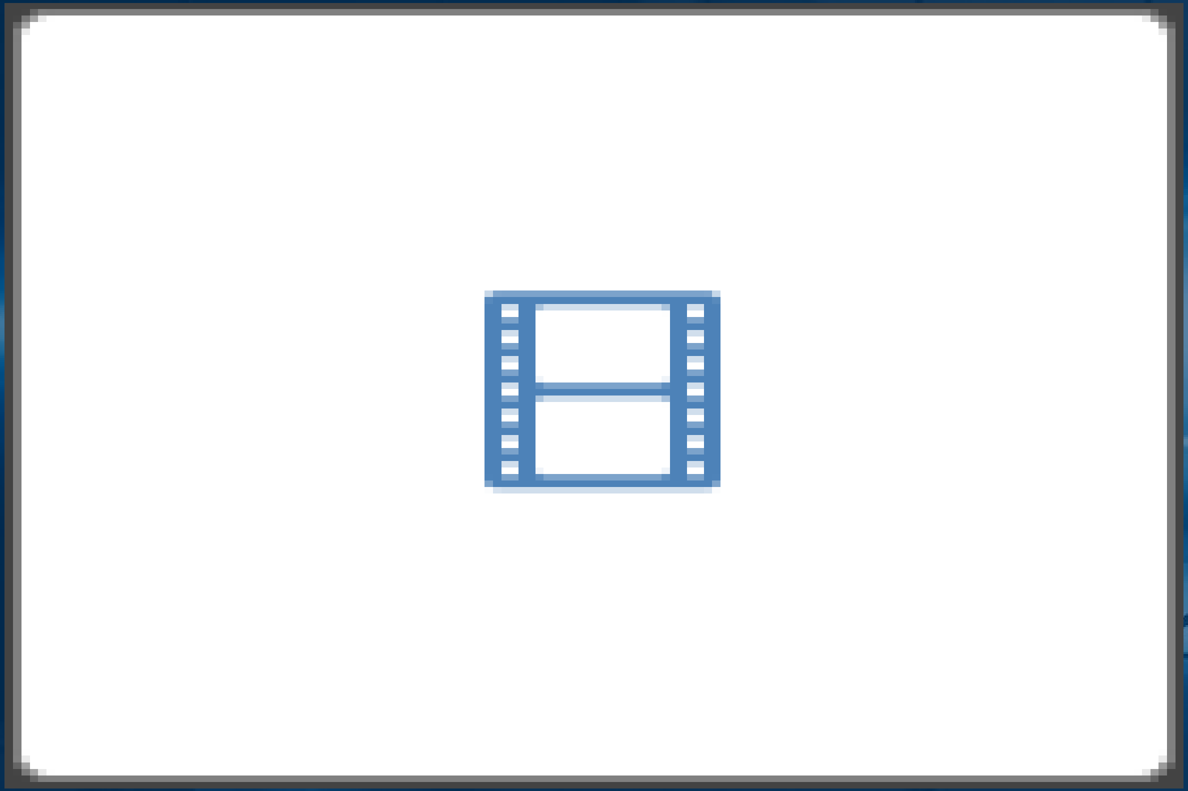
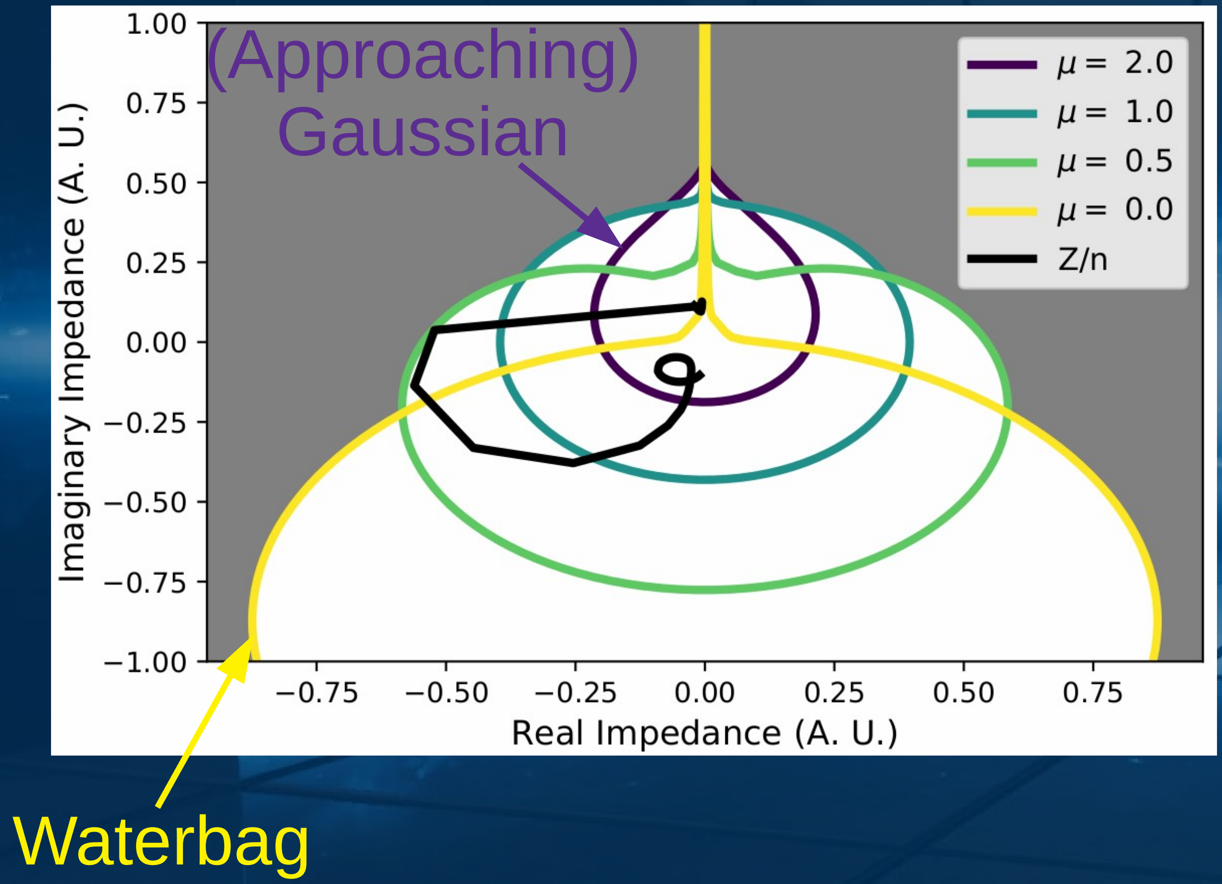
Coasting Beam Approximation



- For a coasting beam, the region of stability can be calculated for different values of μ
- For microwave instability this is a good approximation for bunched beams
- If the impedance fits in the white region, the beam should be stable otherwise it may go unstable

Longitudinal Instability

Coasting Beam Approximation



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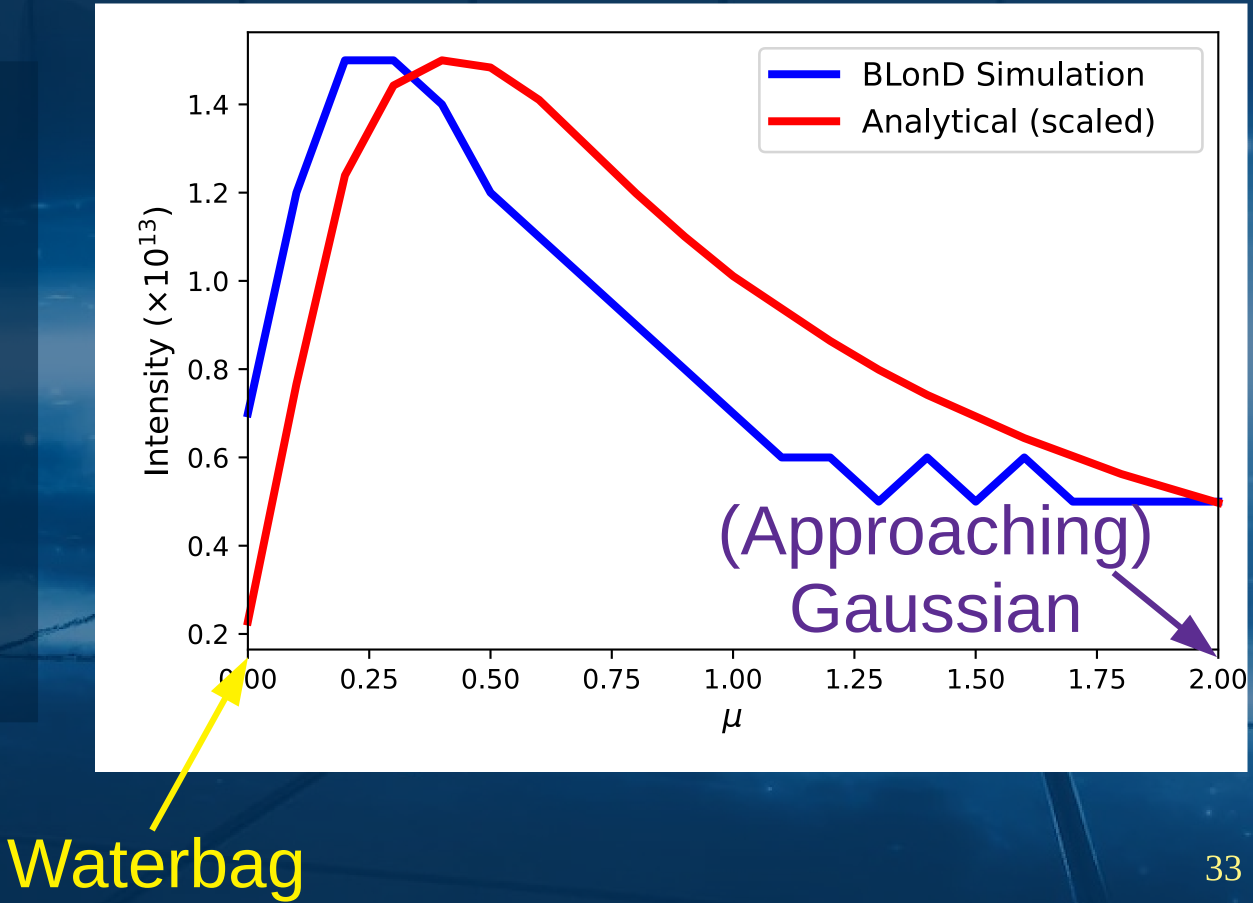
Comparison With Tracking

- Intensity threshold as a function of μ at flat top
- Maximum stable intensity predicted at μ = 0.4 for a **coasting beam**
- Tracking simulations in BLonD with a **bunched beam** and fixed matched area show good agreement



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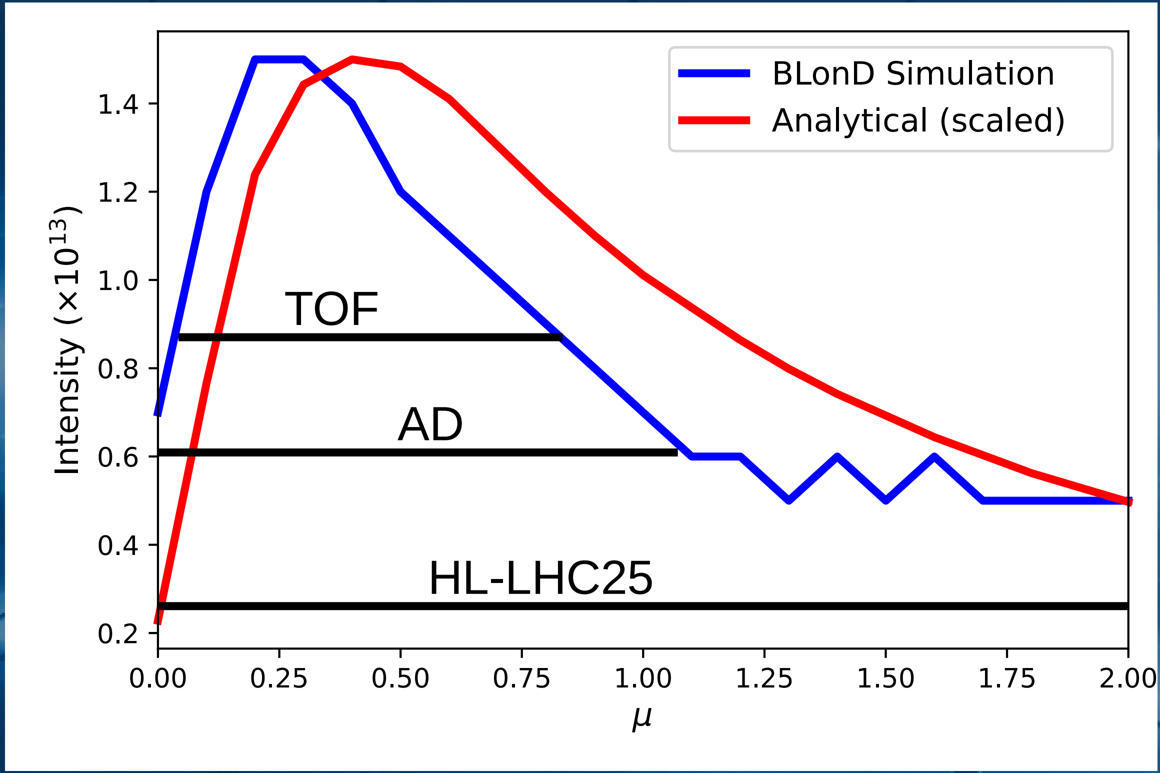
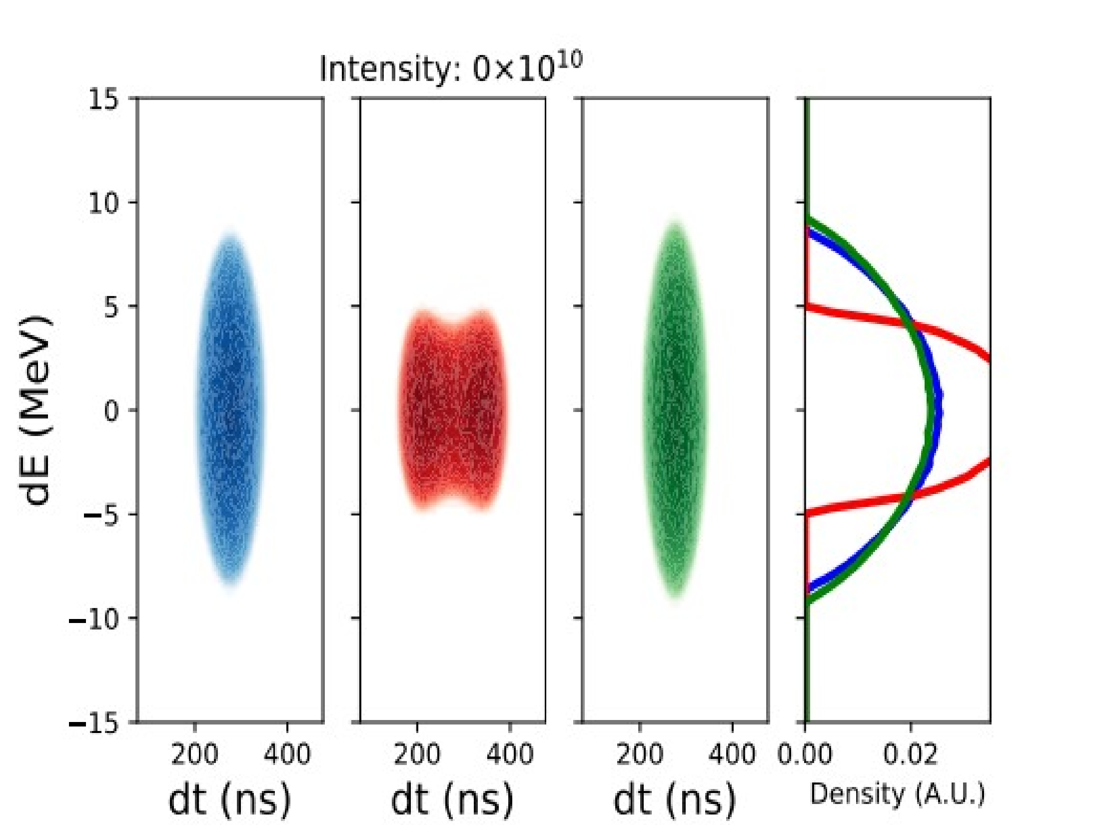


Effect of RF Harmonics and Voltages

10 kV at h=1, 0 kV at h=2

6 kV h=1, 4 kV h=2, Bunch Shortening



6 kV h=1, 4 kV h=2, Bunch Lengthening

- Longitudinal distribution and intensity are not the only factors in stability
- Adjusting the RF voltage and harmonics can act to raise or lower the stability threshold
- Large energy spread is preferable

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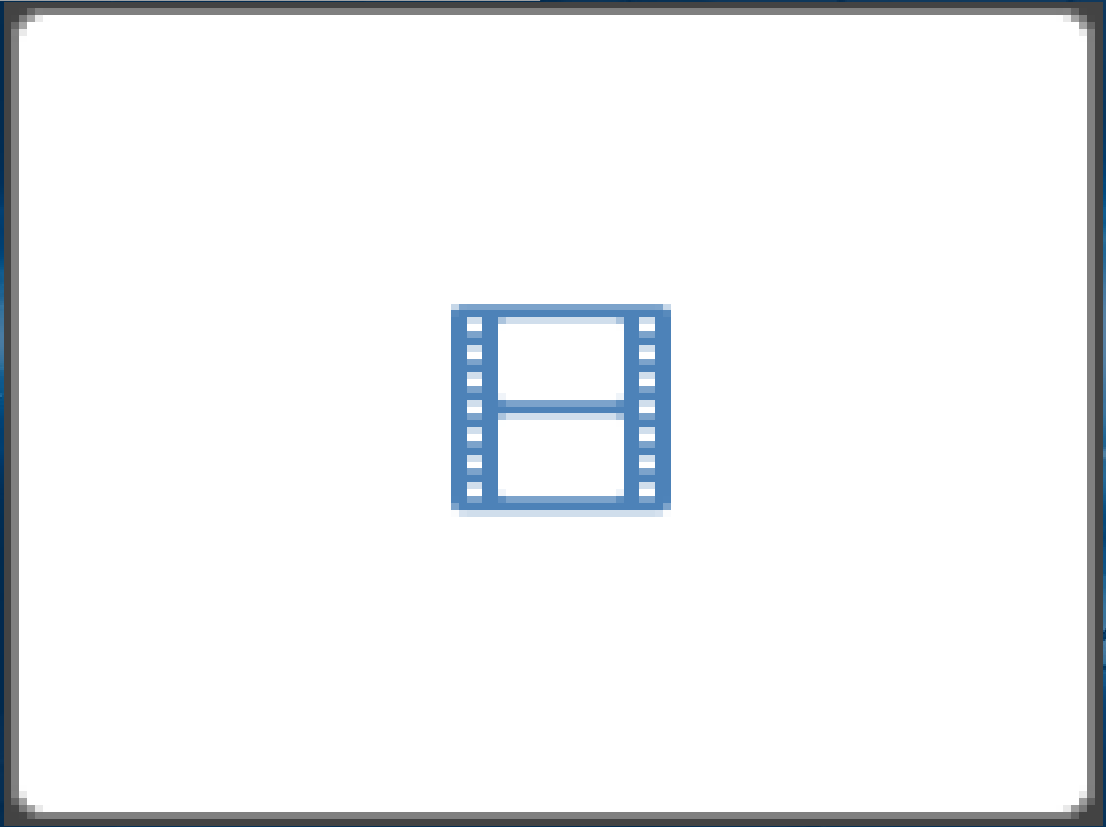

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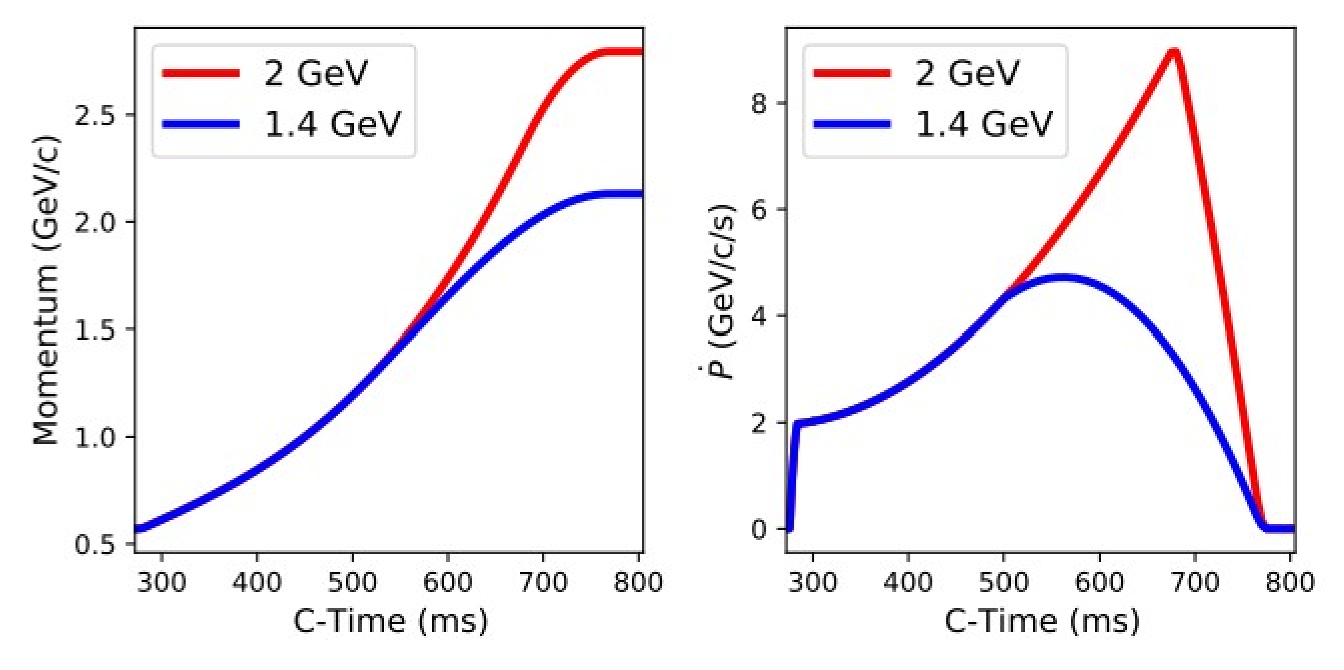
Longitudinal Instability

- Beam interactions with the environment can cause the beam to become unstable, leading to uncontrolled emittance blow-up and/or beam loss
- The impedance of the Finemet cavities is the dominant contribution to the impedance, and can trigger microwave instability
- Careful tuning of the longitudinal distribution and choosing the right voltage settings is necessary for stability at high intensity

Operational Beam Production

Magnetic Cycles

- Two magnetic cycles
- 1.4 GeV kinetic energy to ISOLDE
- 2 GeV kinetic energy to the PS



Challenging Cycle Types

- ISOLDE:

  High intensity, medium emittance, 1.4 GeV

- HL-LHC25:

  Low intensity, large emittance, 2 GeV

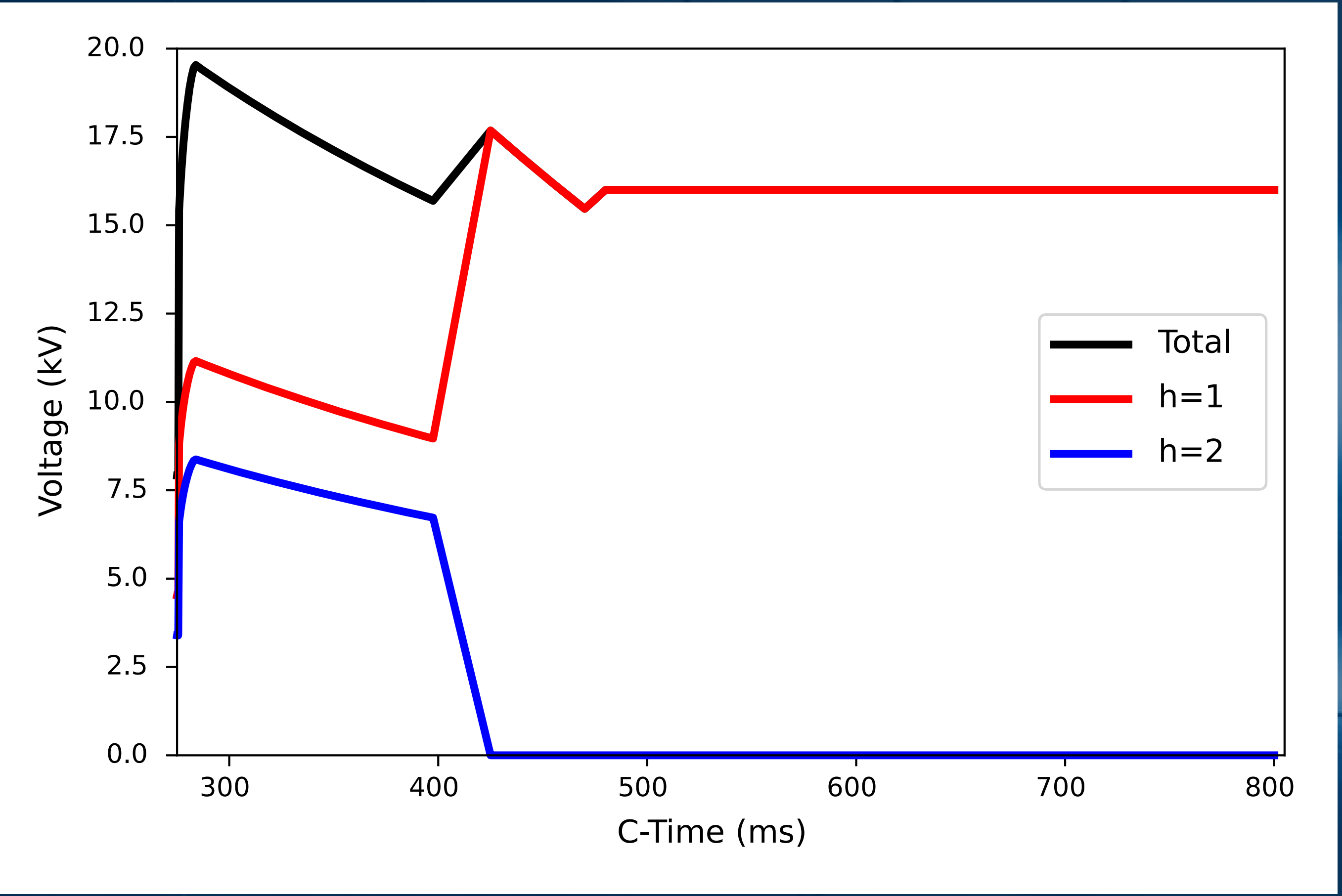
- MTE:

  Medium intensity, large emittance then splitting, 2 GeV

- TOF:

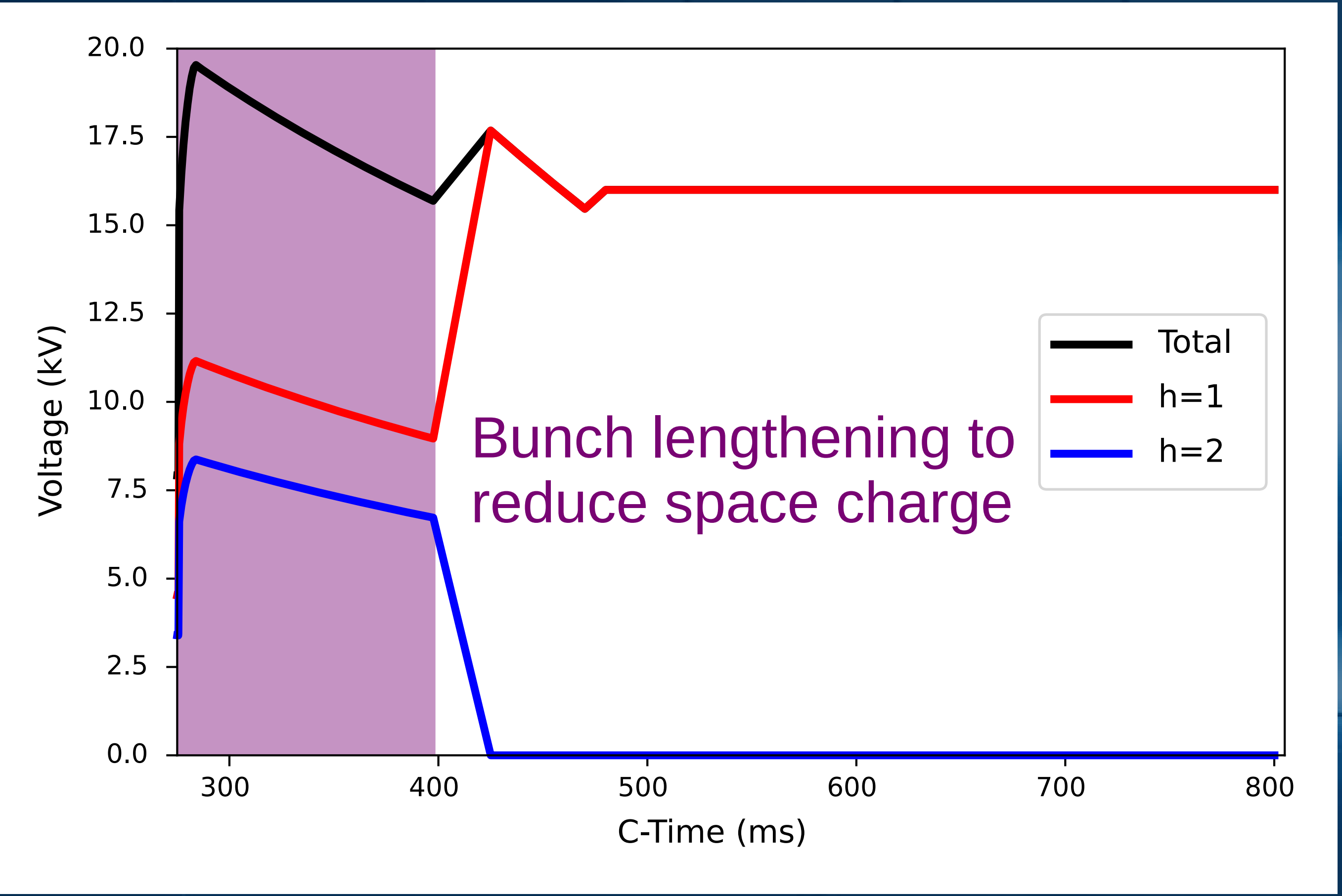
  High intensity, medium emittance, 2 GeV

Operational Beam Production
ISOLDE



- ε_l=1.7 eVs injection
- ε_l=1.8 eVs extraction
- 850x10^{10} Protons per ring
- 1.4 GeV extraction kinetic energy

Operational Beam Production
ISOLDE



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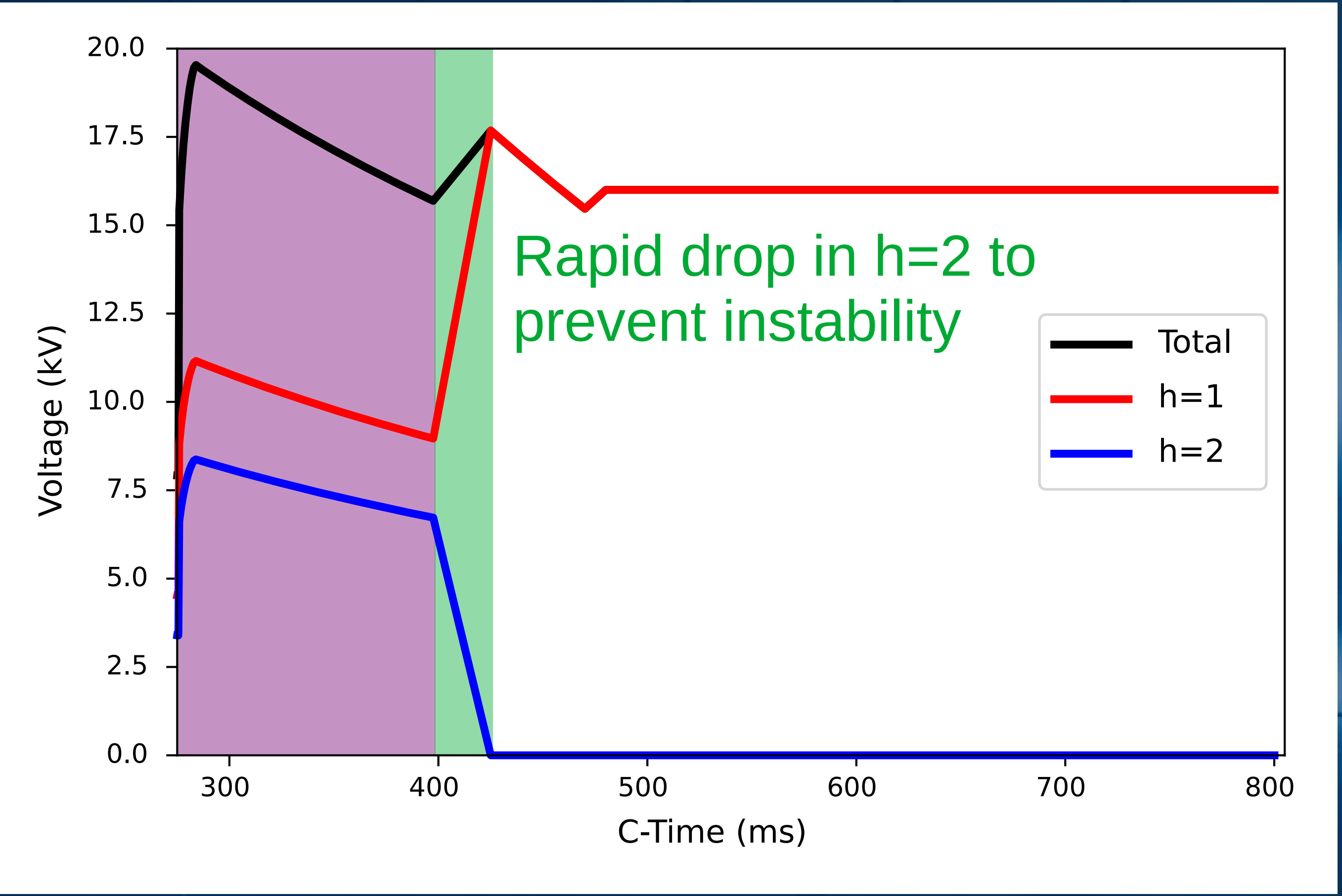

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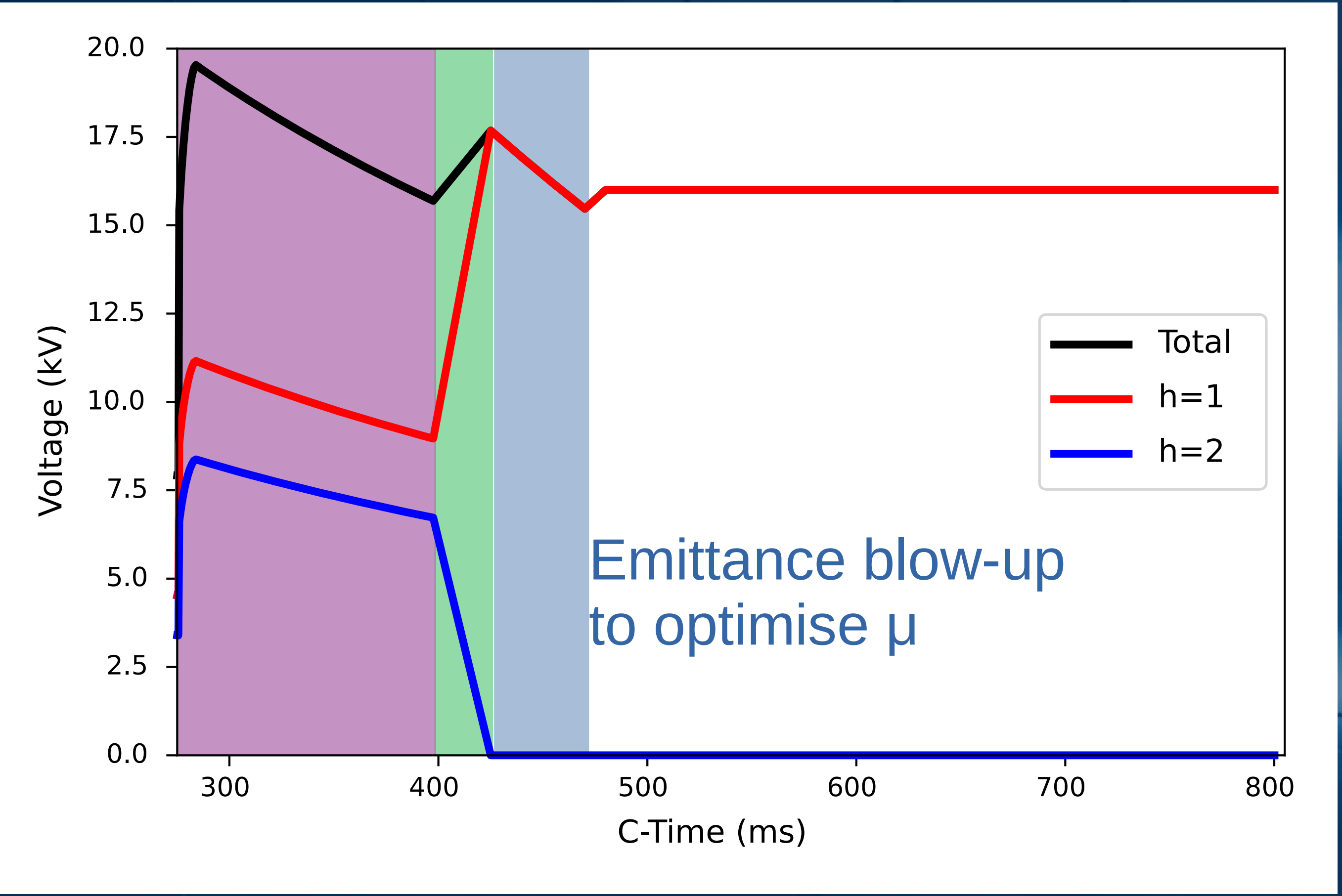

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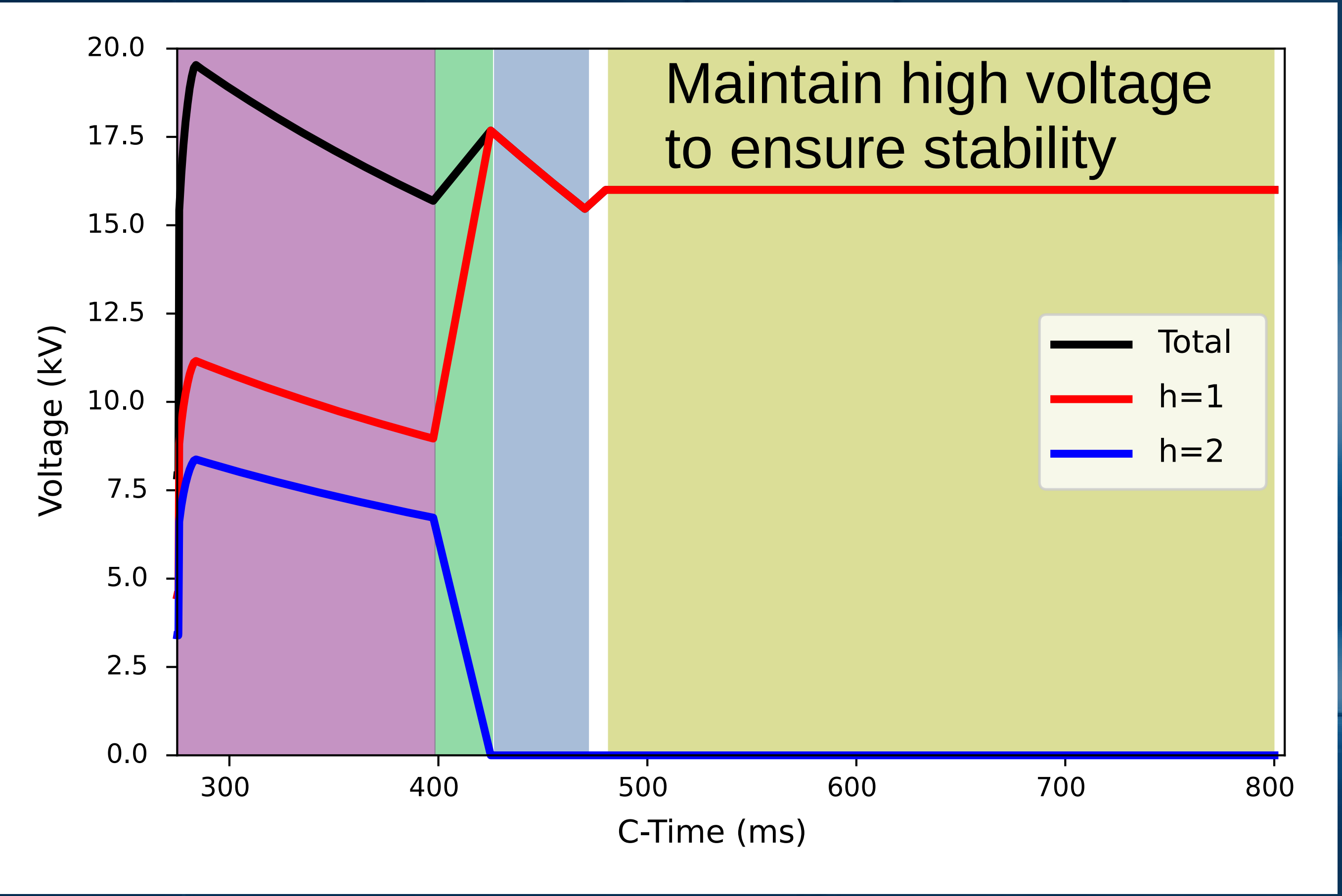

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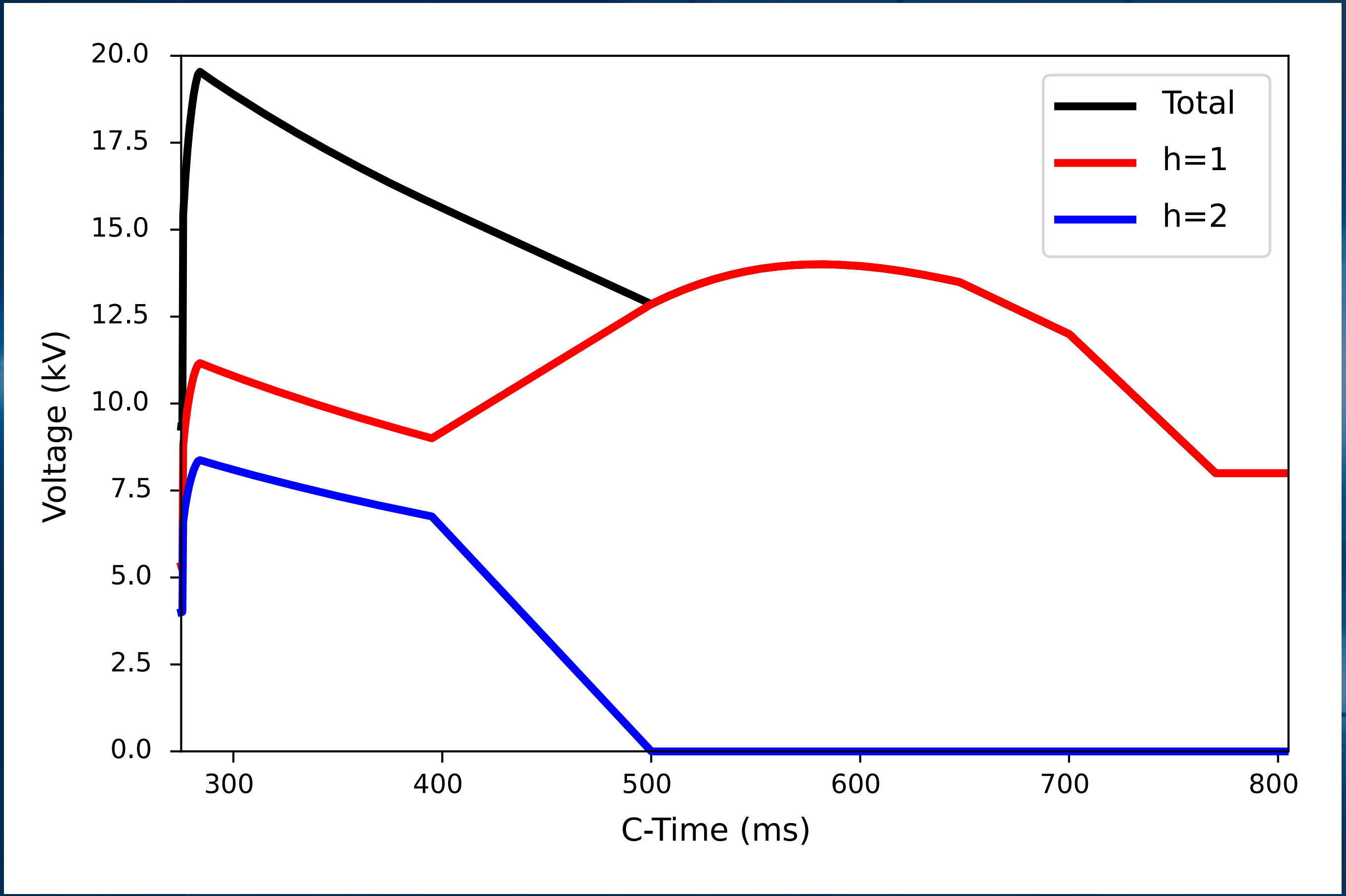
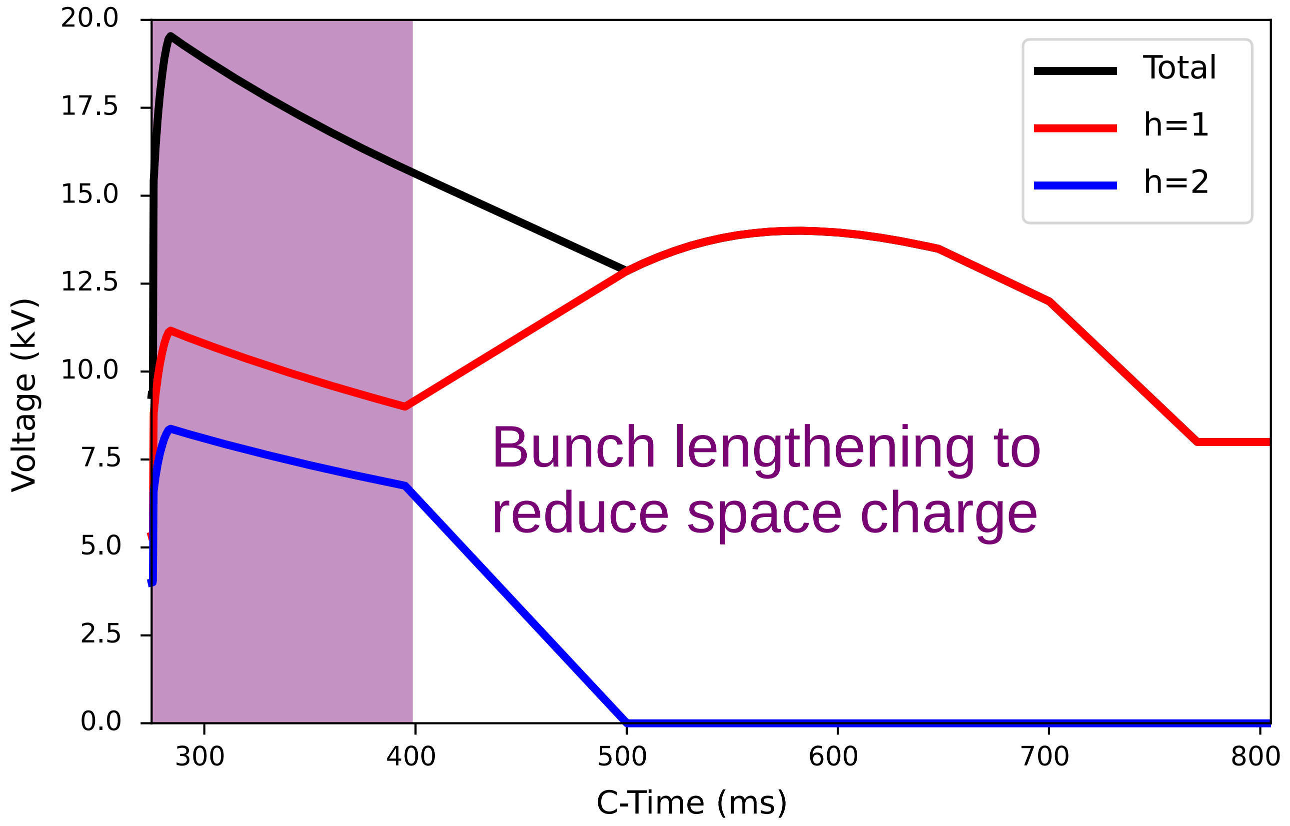
HL-LHC25



- ε_l=1.9 eVs injection
- ε_l=3 eVs extraction
- 350x10^{10} Protons per ring
- 2 GeV extraction kinetic energy

Operational Beam Production
HL-LHC25



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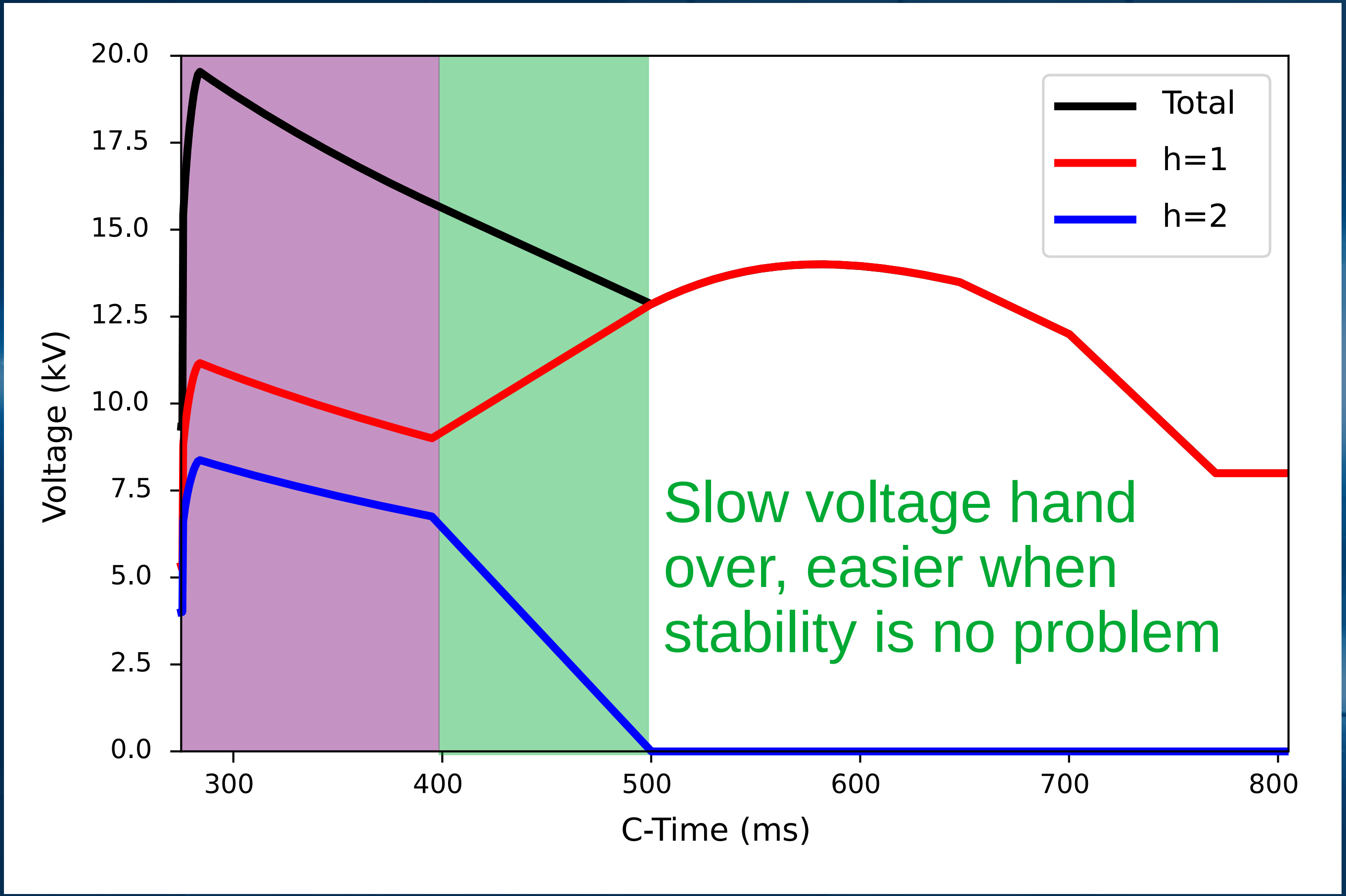

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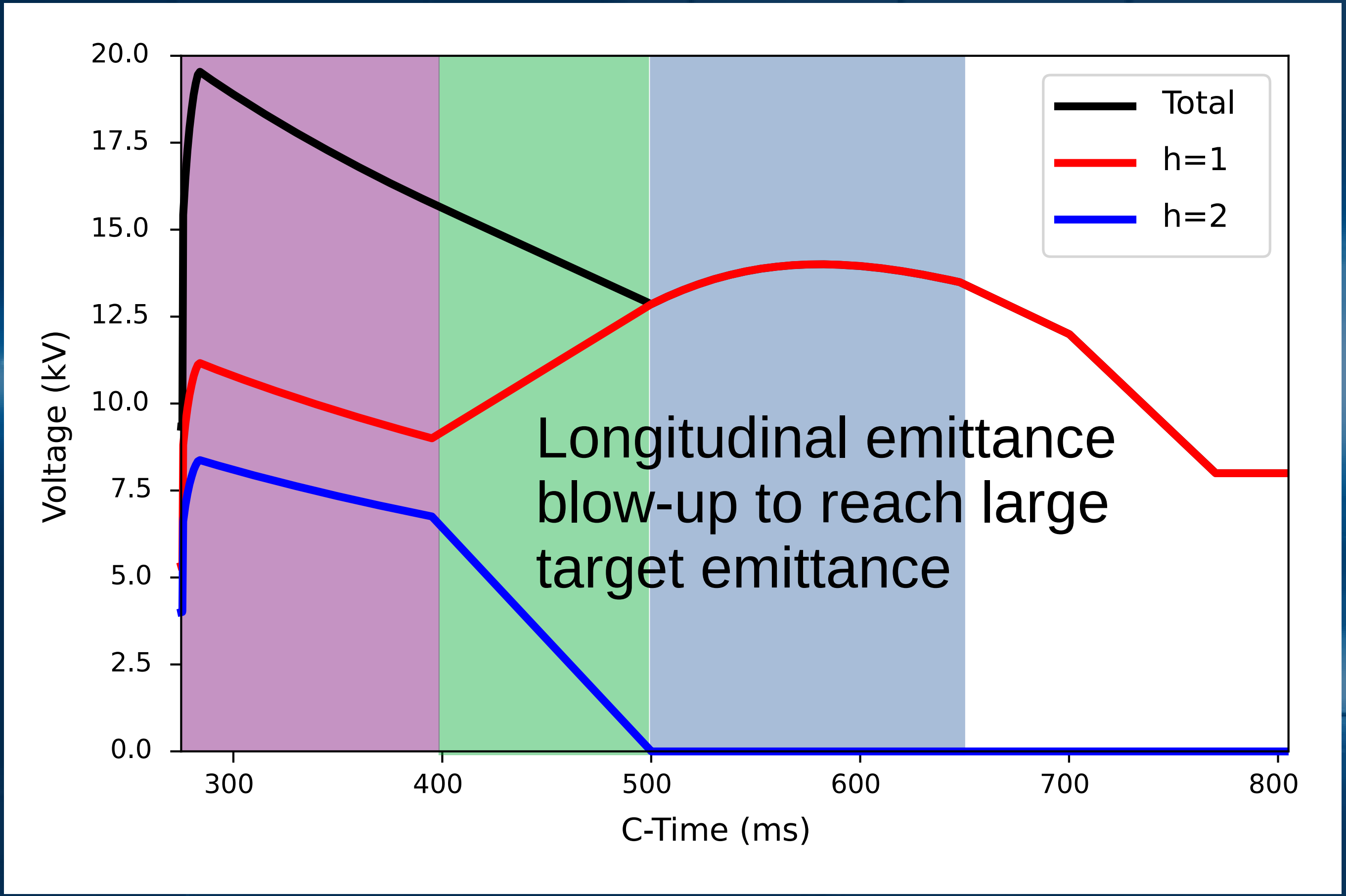

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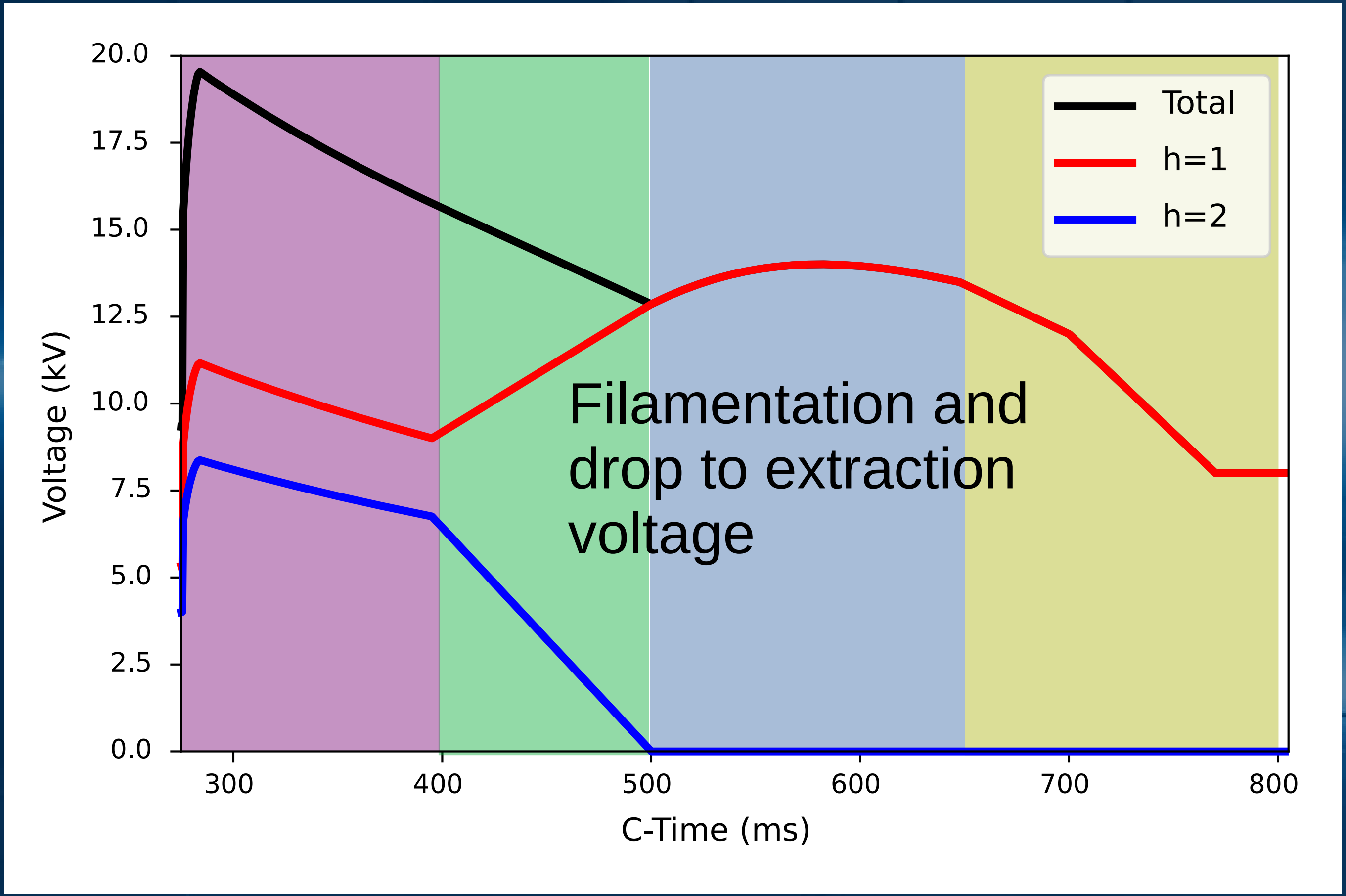

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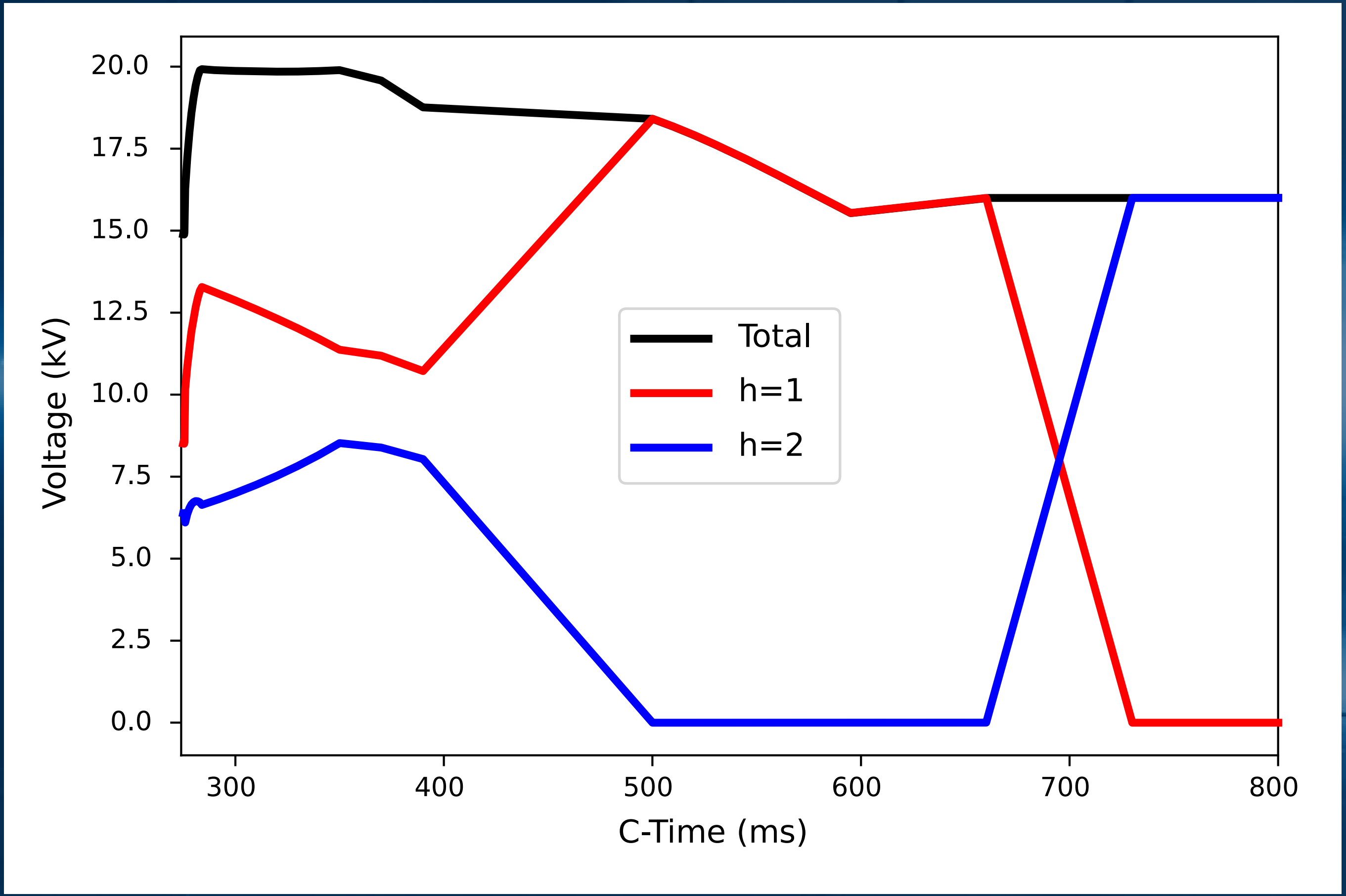
MTE



- ε_l=2.2 eVs injection (single bunch)
- ε_l=1.3 eVs extraction (two bunches)
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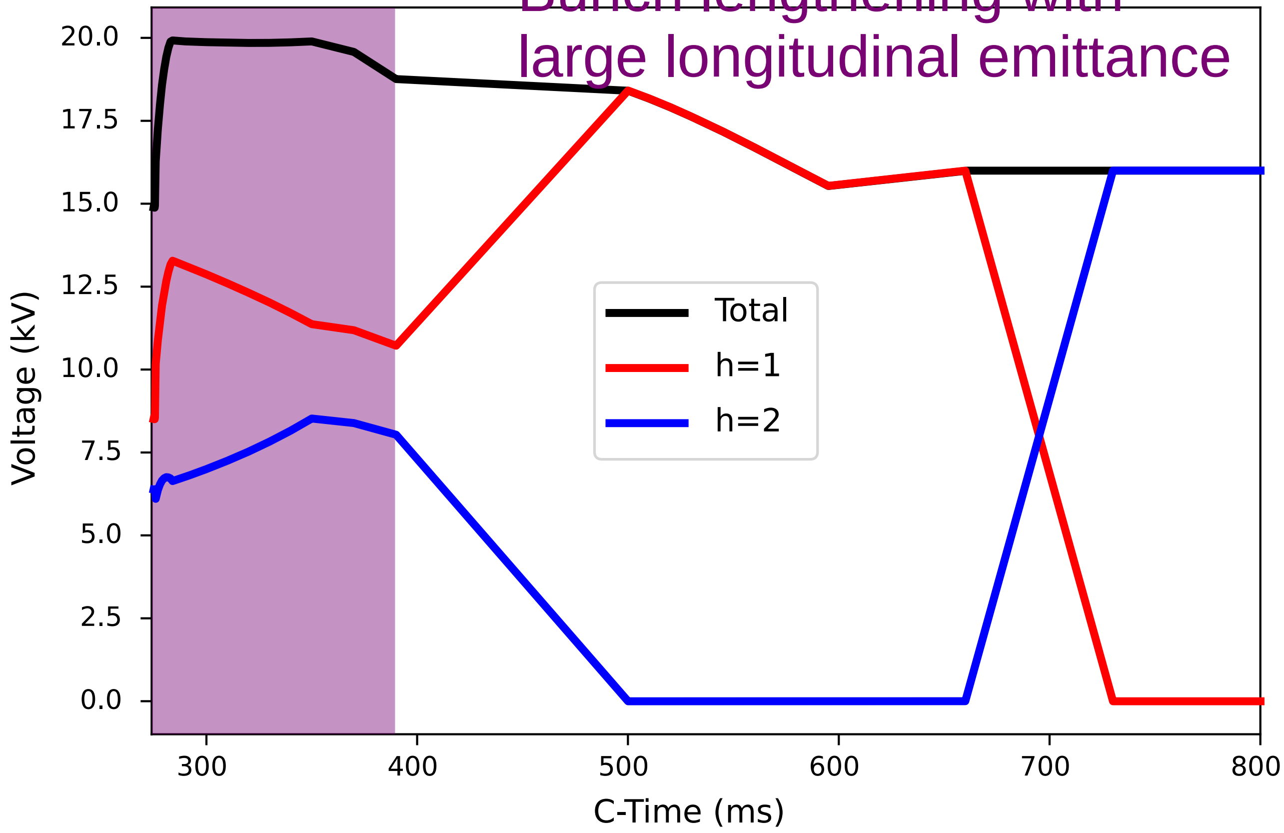
Operational Beam Production

MTE

Bunch lengthening with large longitudinal emittance



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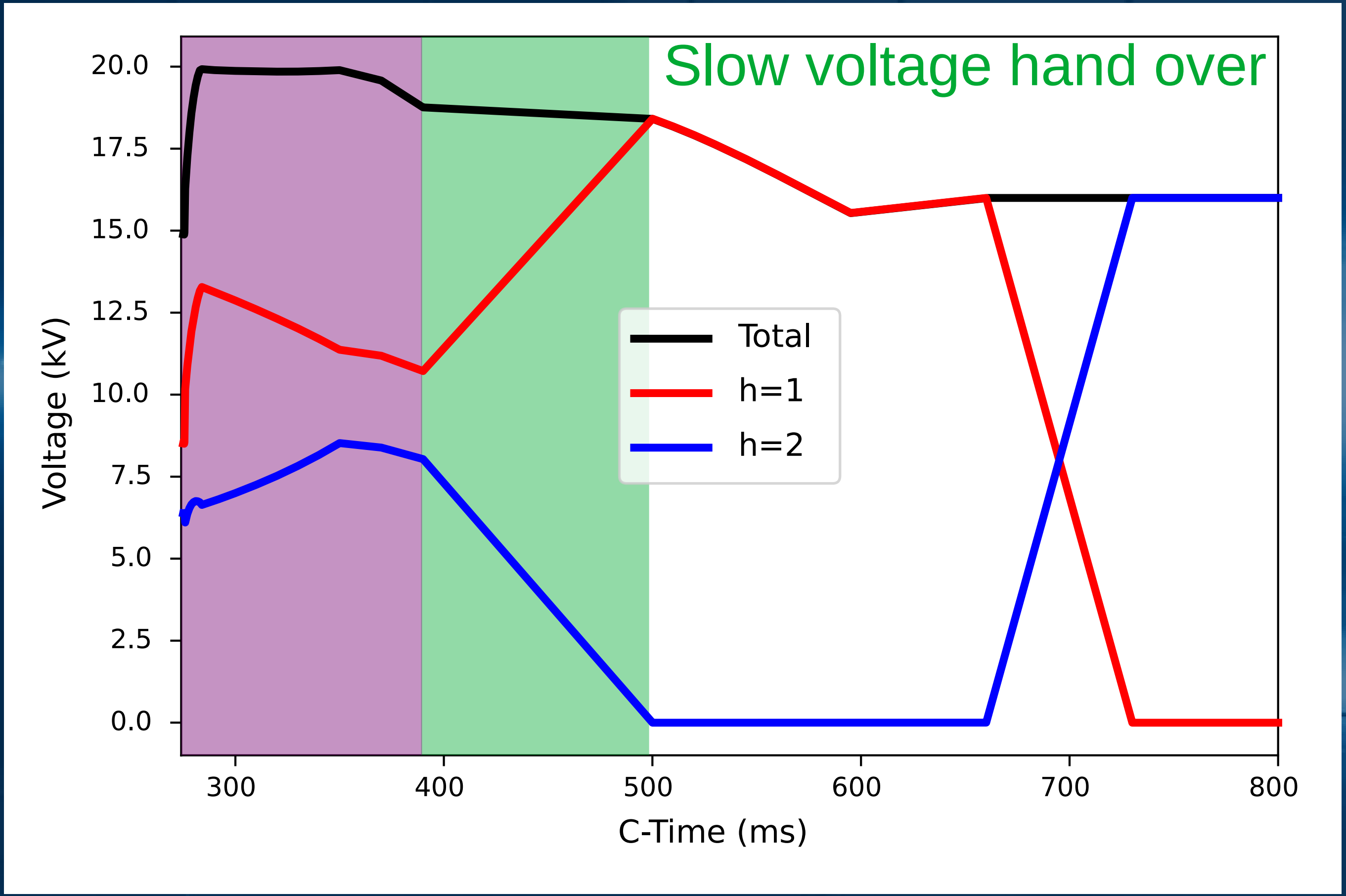

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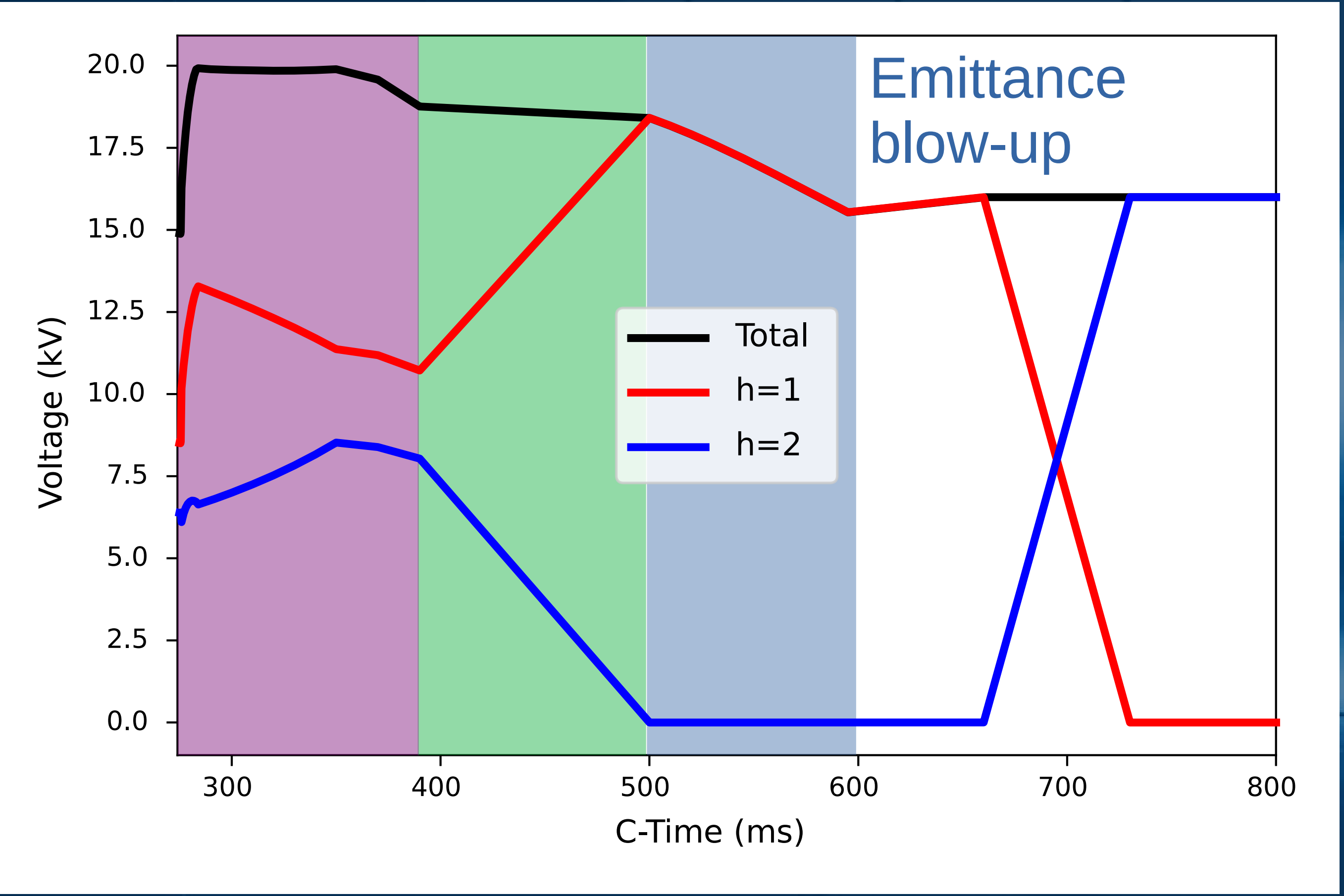

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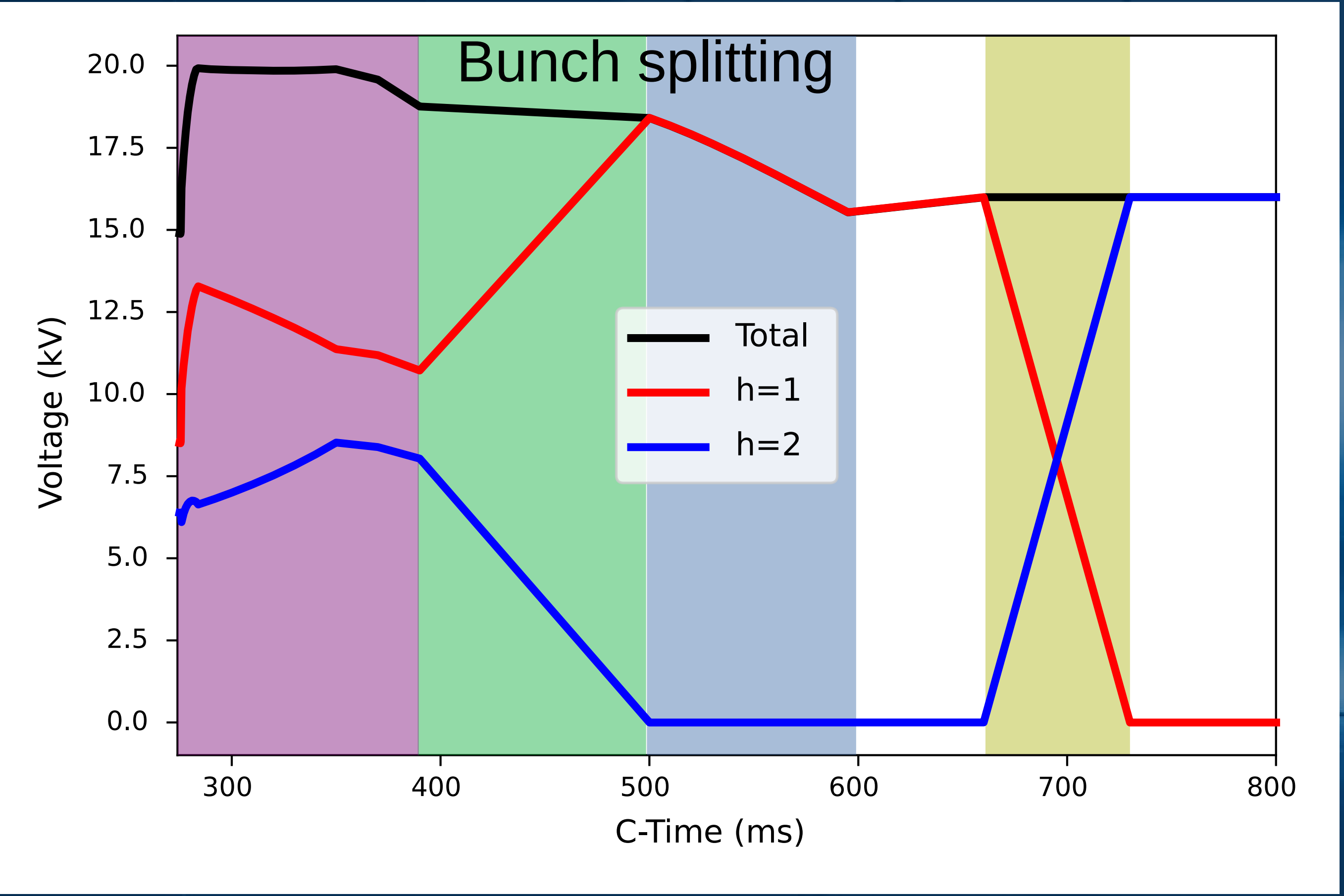

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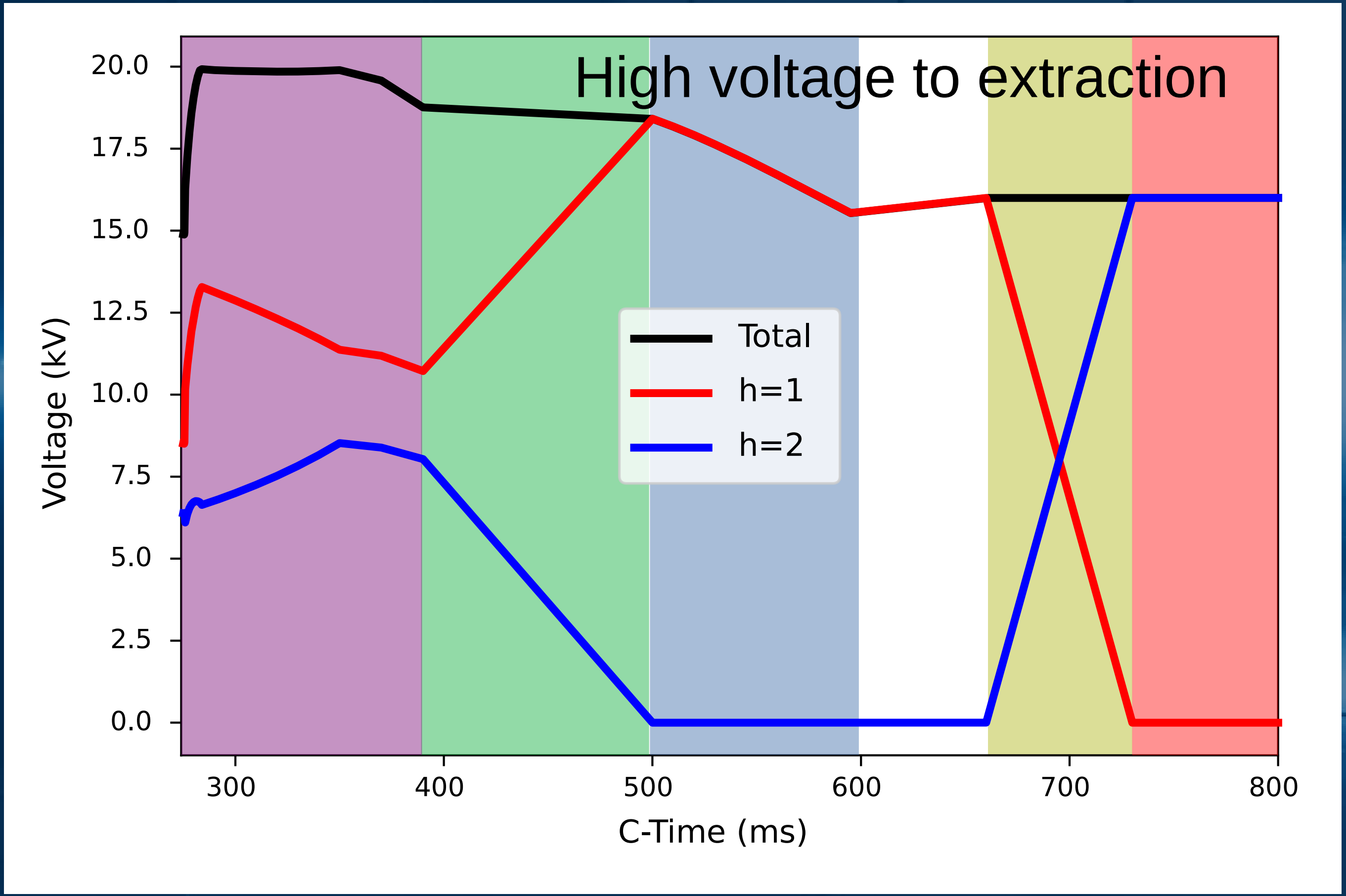

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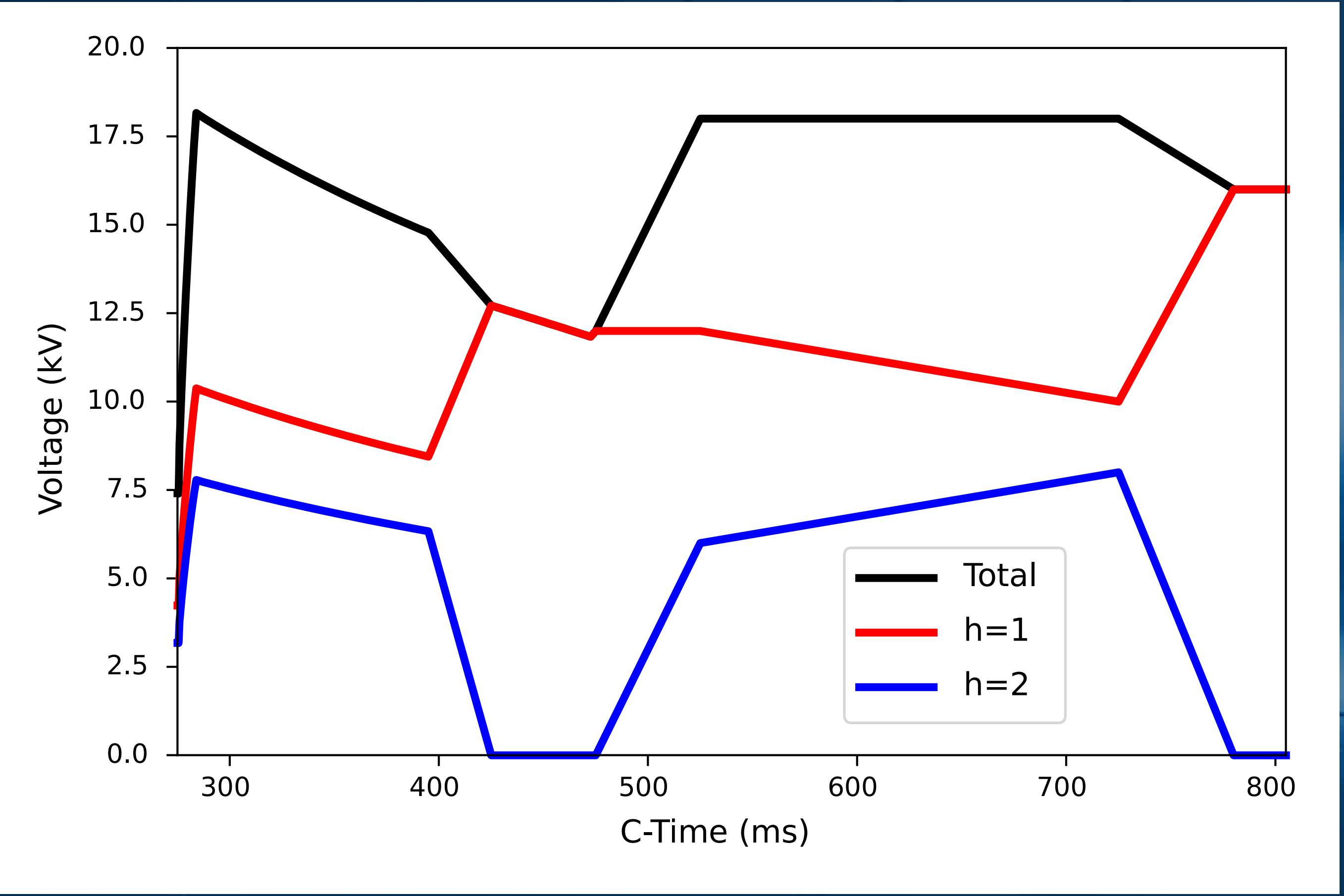
Operational Beam Production
TOF



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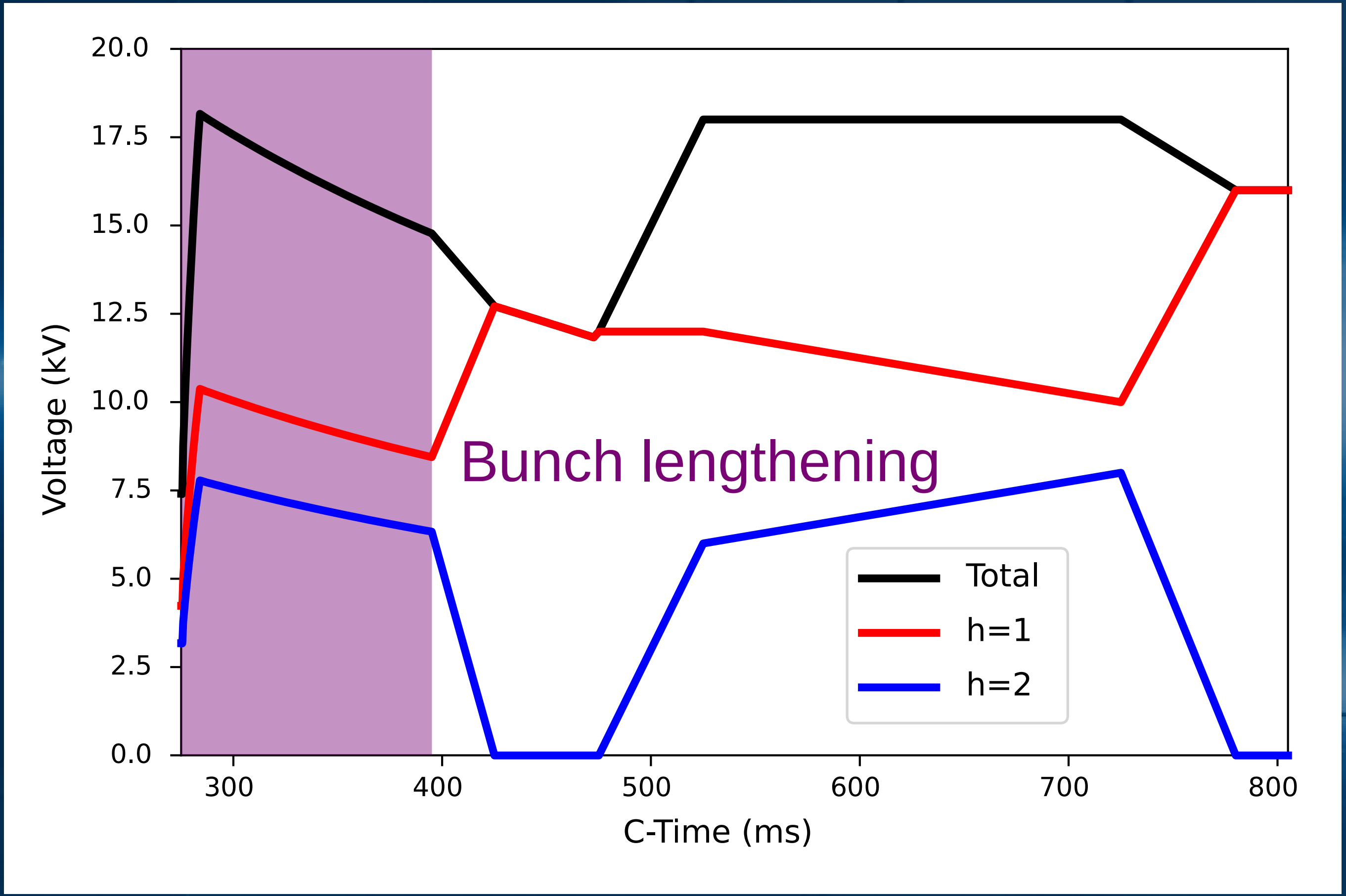
Operational Beam Production
TOF



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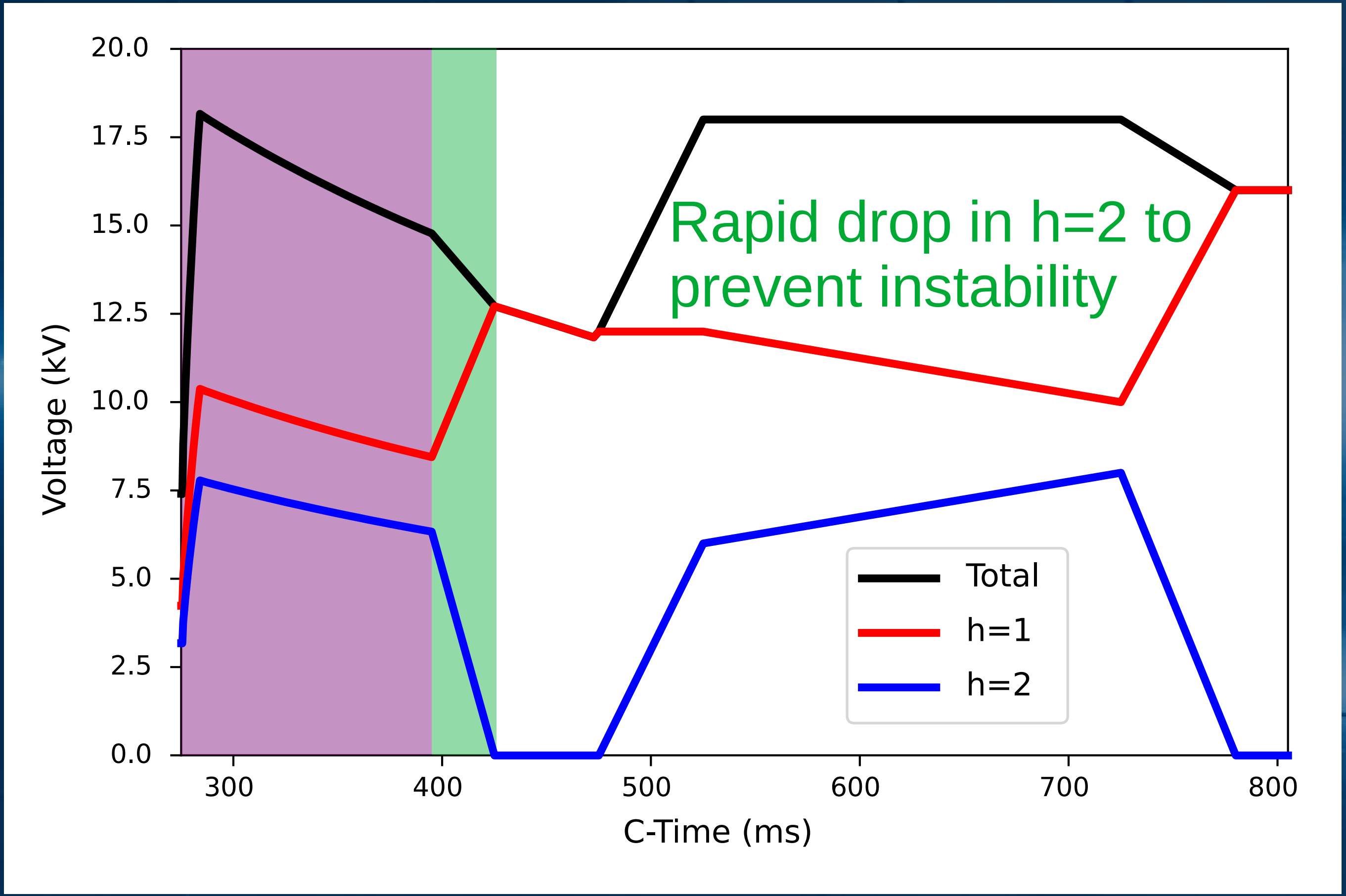

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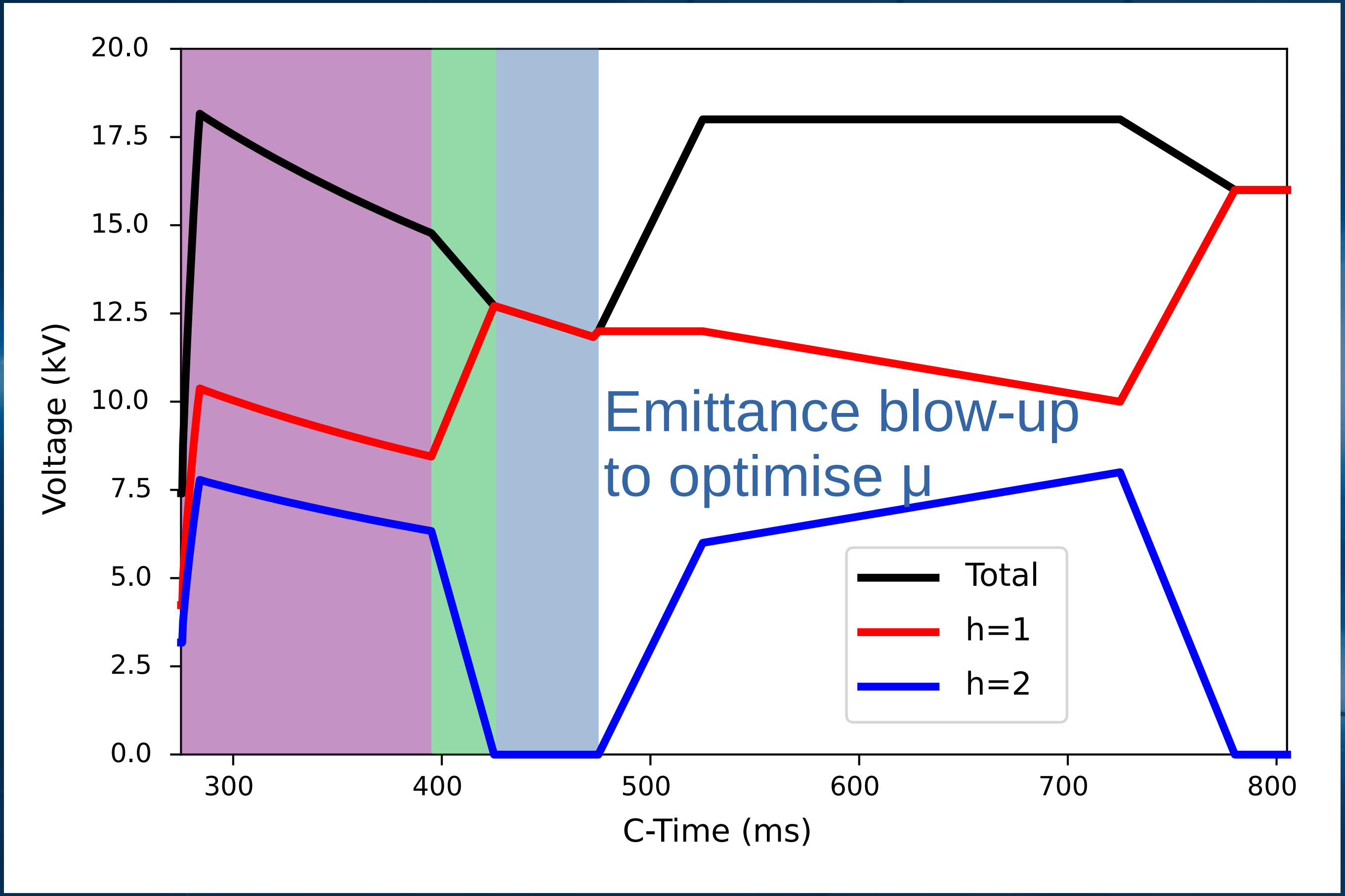
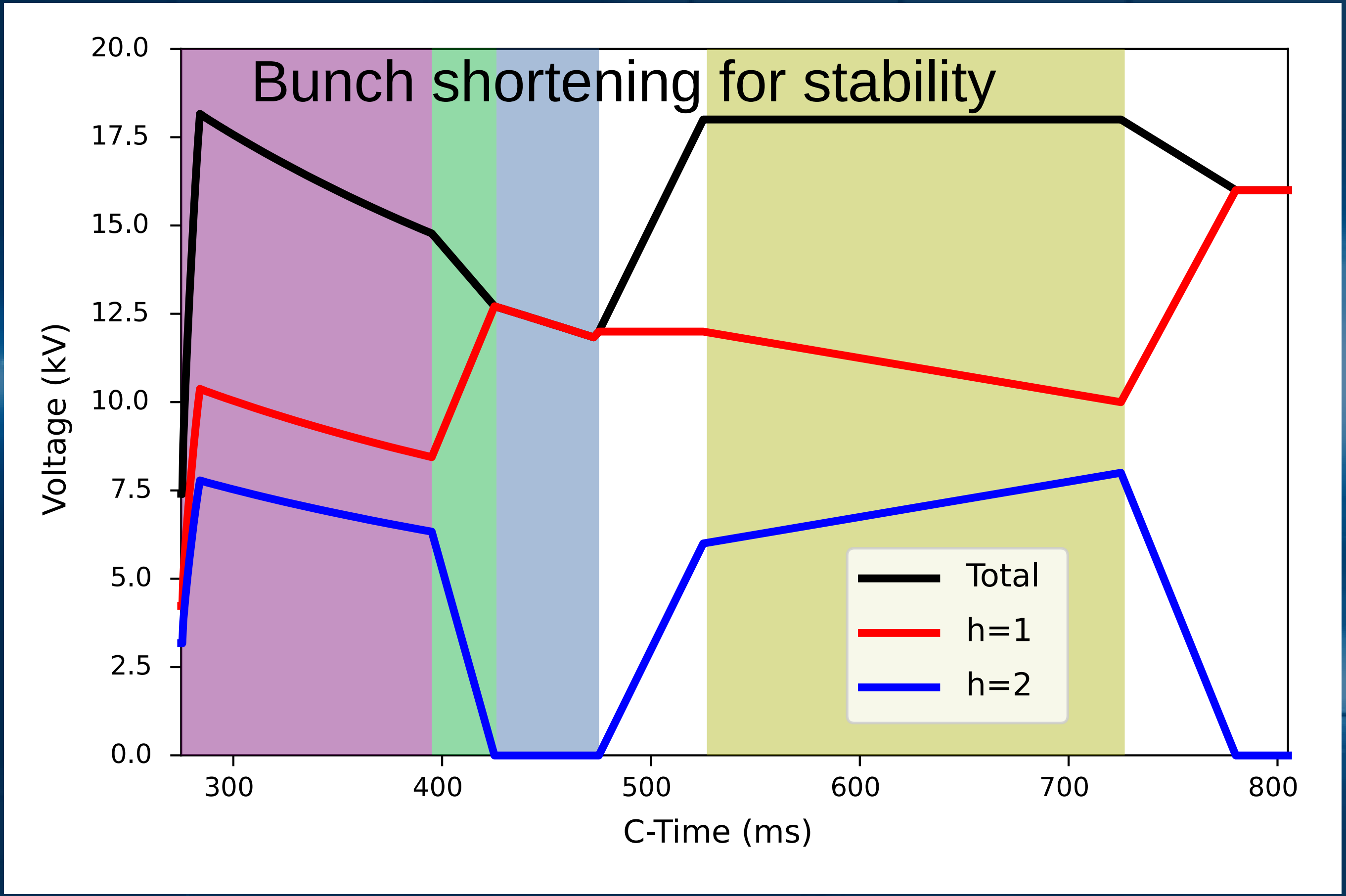
Operational Beam Production
TOF



- ε_l=1.6 eVs injection
- ε_l=1.7 eVs extraction
- 850x10^{10} Protons per ring
- 2 GeV extraction kinetic energy

Operational Beam Production
TOF



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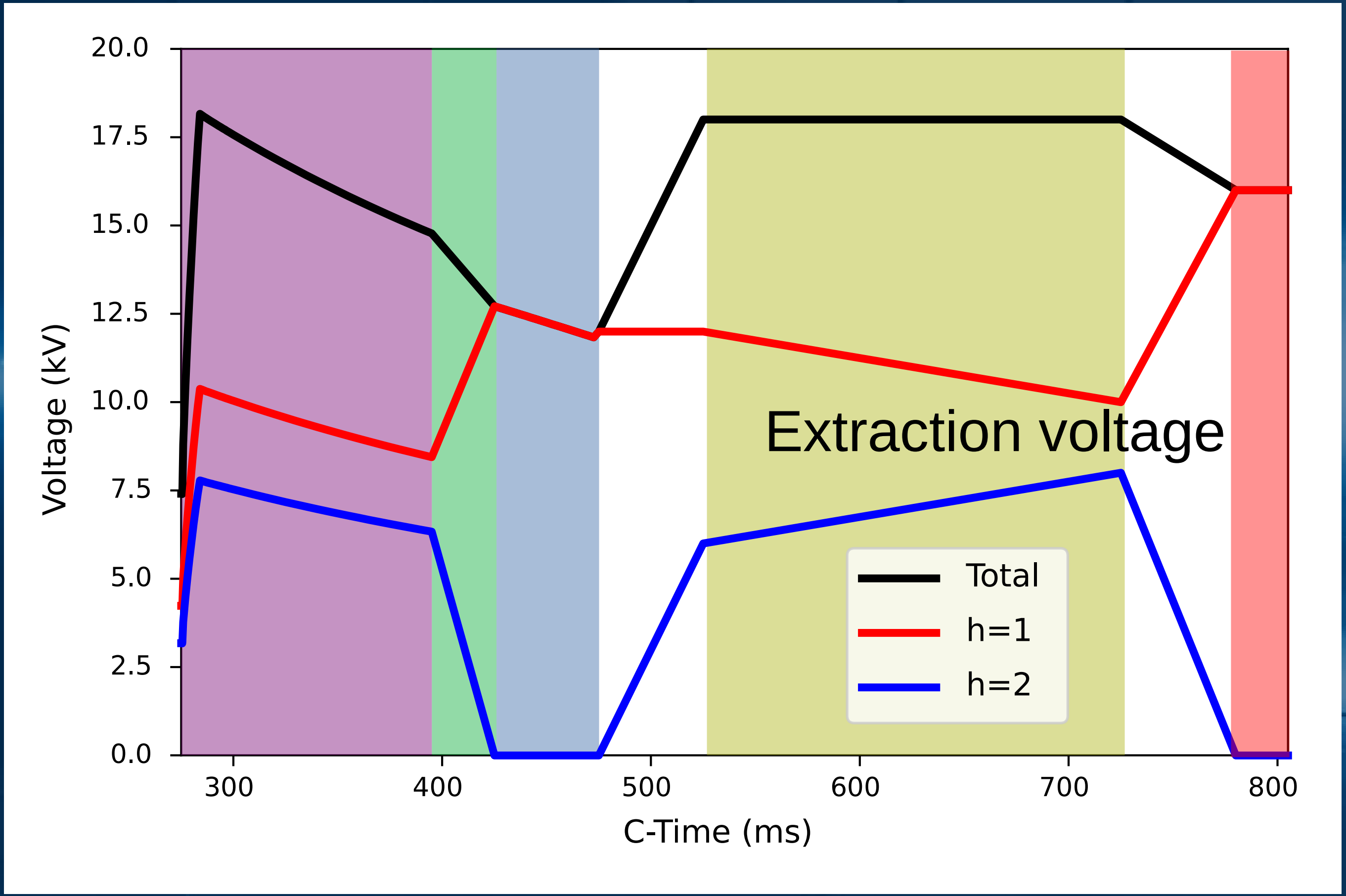
Operational Beam Production
TOF



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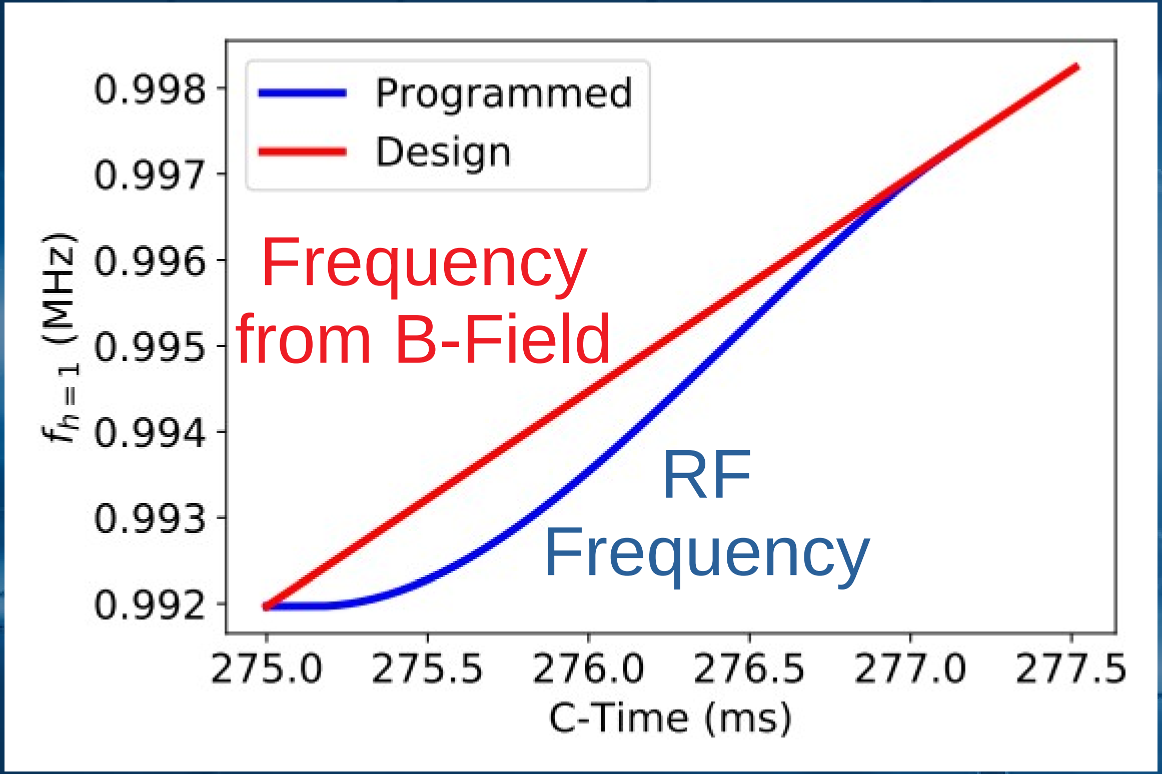
- ε_l=1.7 eVs extraction
- 850x10^{10} Protons per ring
- 2 GeV extraction kinetic energy

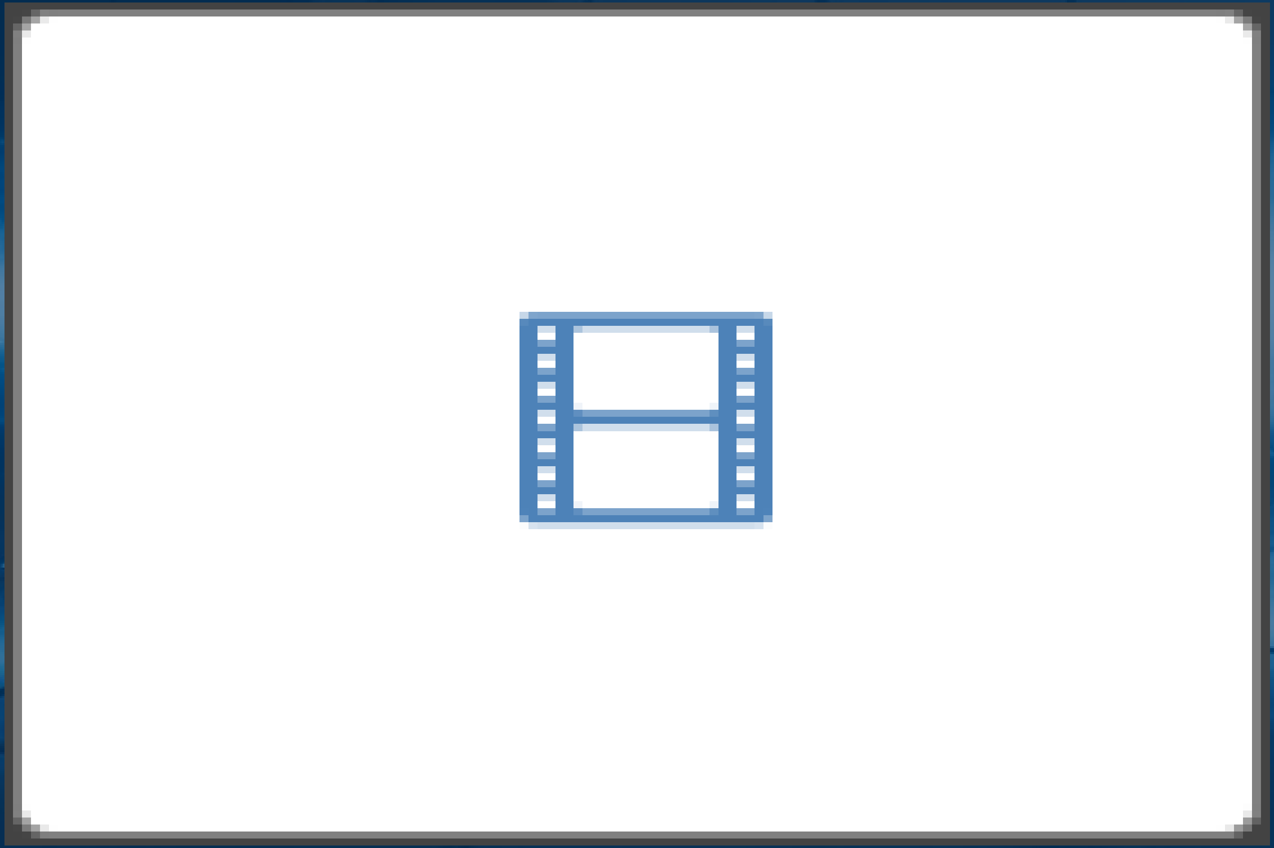
Injection on the Ramp

Injection on the Ramp
RF Frequency

- Pre-LS2, injection on the ramp was used to reduce the impact of space charge by increasing β as quickly as possible
- Injecting on the ramp was originally planned for post-LS2
- During injection the RF frequency is fixed, and then returns to the frequency derived from the magnetic field afterwards

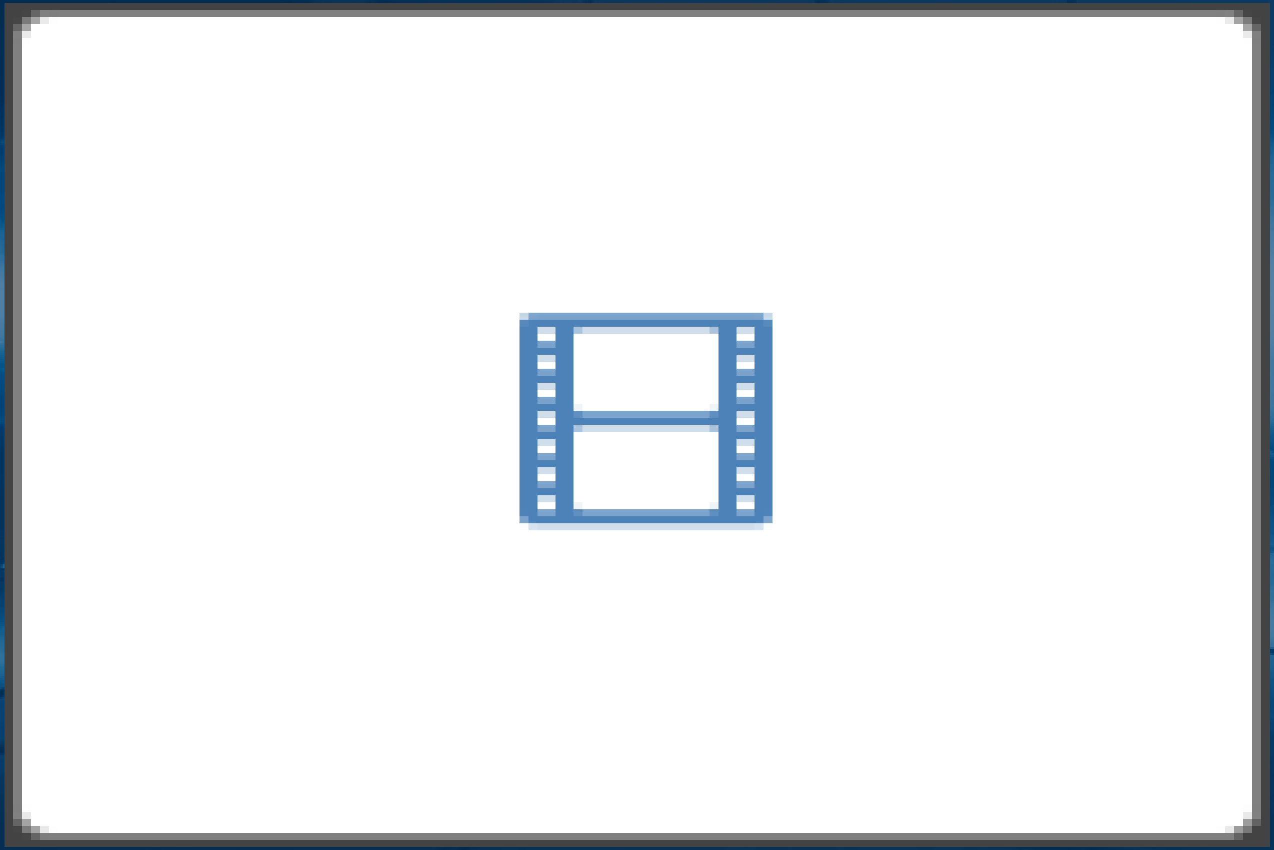


RF Frequency Following Magnetic Field



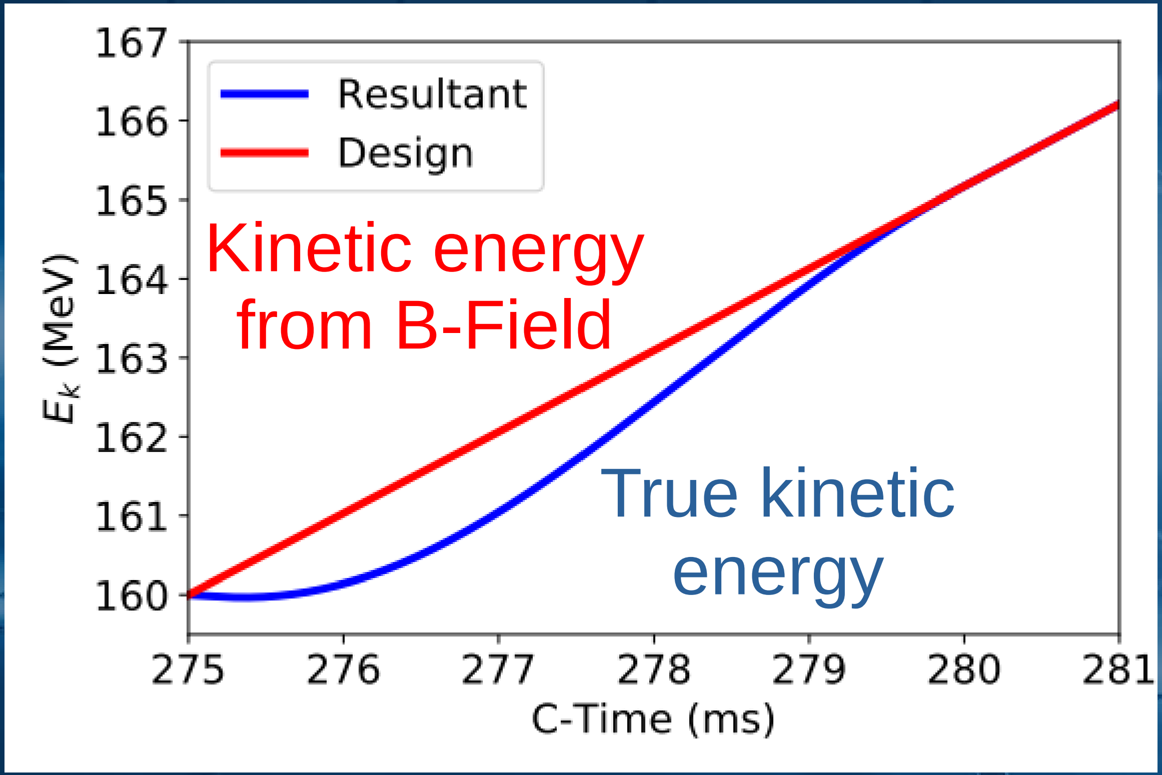
Injection on the Ramp

RF Frequency Fixed



Kinetic Energy Calculation

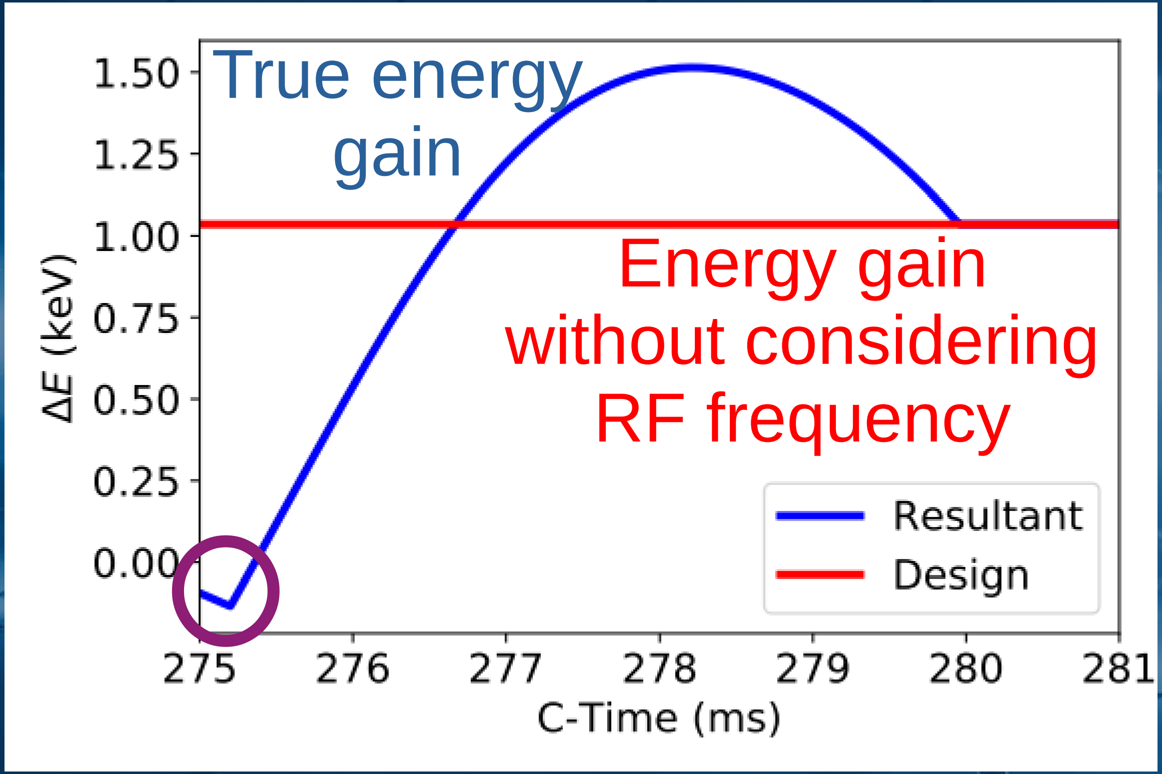
- The kinetic energy of the circulating beam is determined by a combination of the RF frequency and magnetic field



Injection on the Ramp

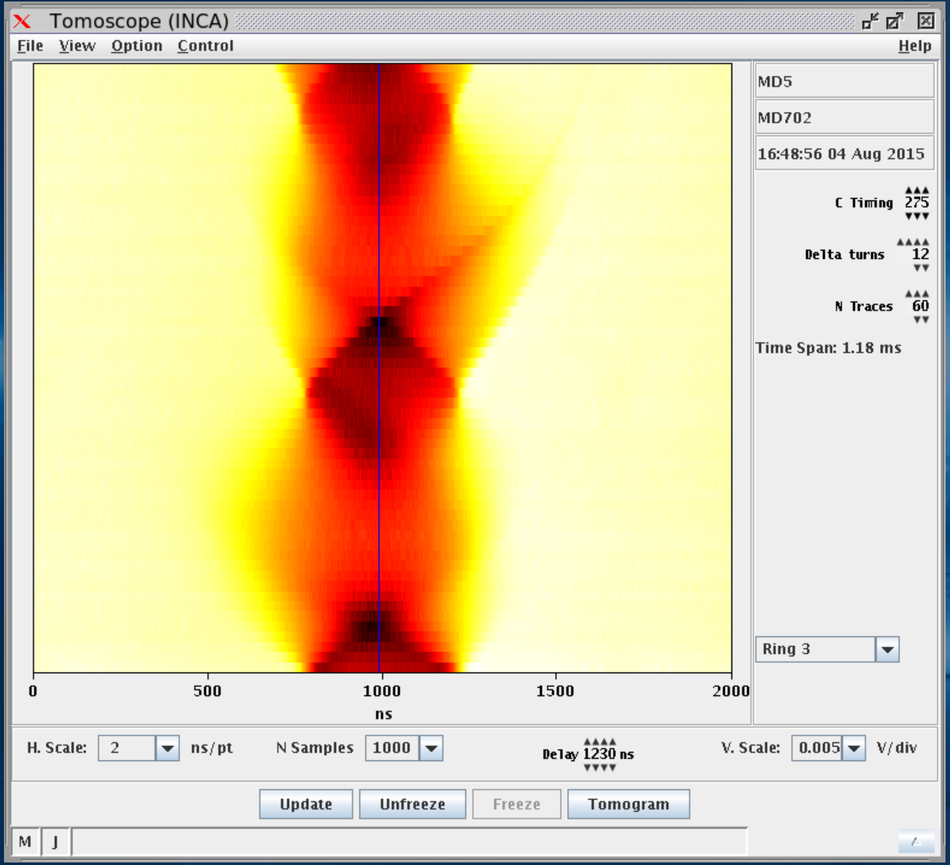
Acceleration

- The kinetic energy of the circulating beam is determined by a combination of the RF frequency and magnetic field
- Fixed RF frequency with increasing magnetic field causes a small deceleration



Injection on the Ramp

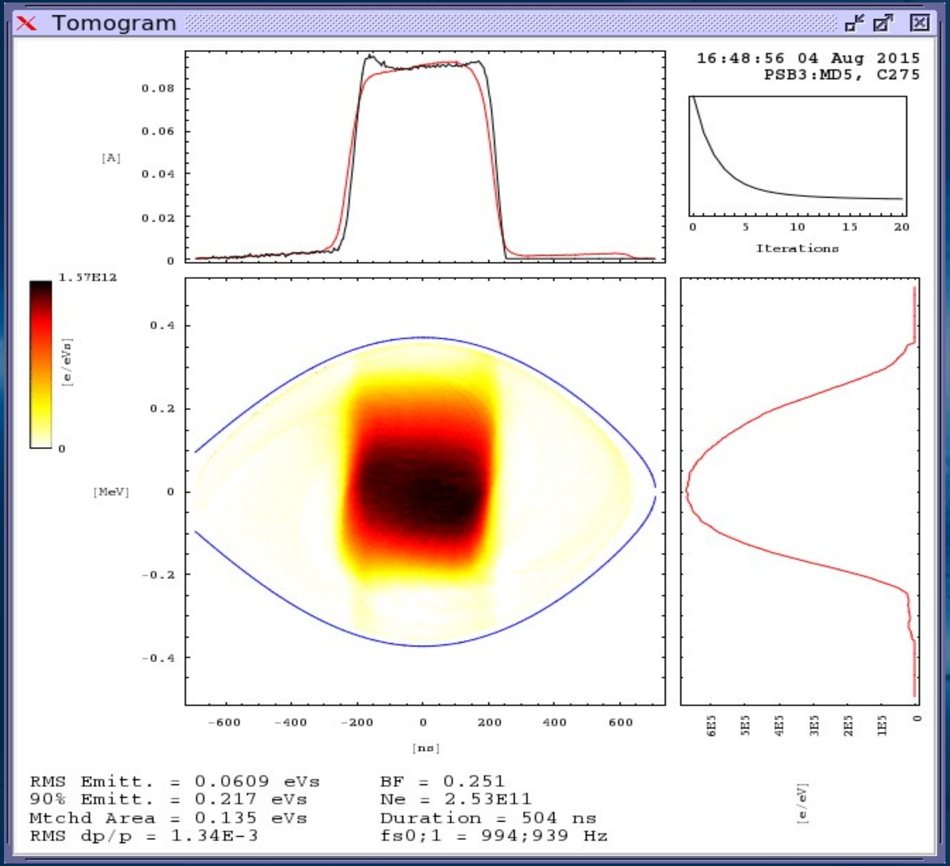
Longitudinal Phase Space Tomography



- Unusual beam dynamics were shown by S. Hancock in 2016 (CERN-ACC-NOTE-2016-0040)

Injection on the Ramp

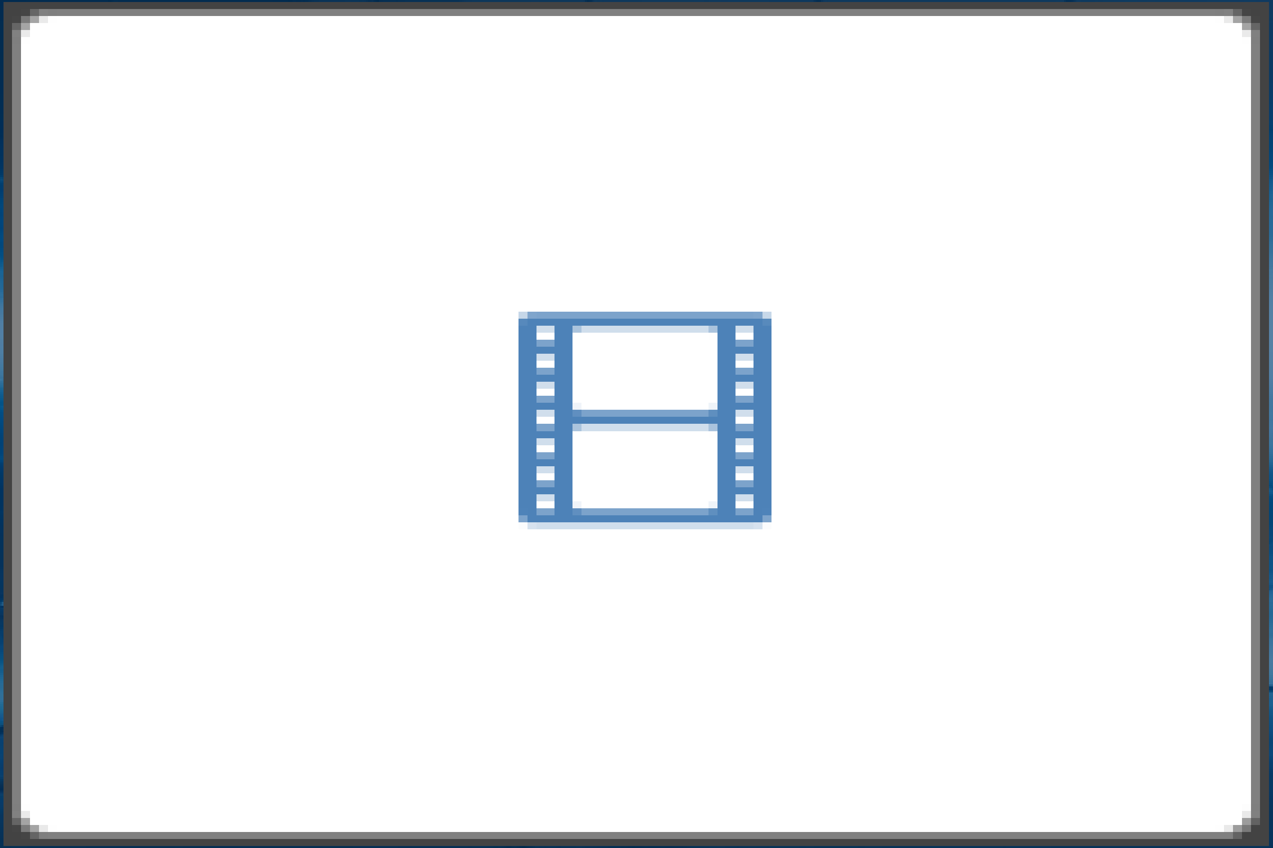
Longitudinal Phase Space Tomography



- Unusual beam dynamics were shown by S. Hancock in 2016 (CERN-ACC-NOTE-2016-0040)
- Inputting a deceleration into the tomoscope allowed an accurate reconstruction of the distribution injected from Linac2

Injection on the Ramp

Return to B-Train

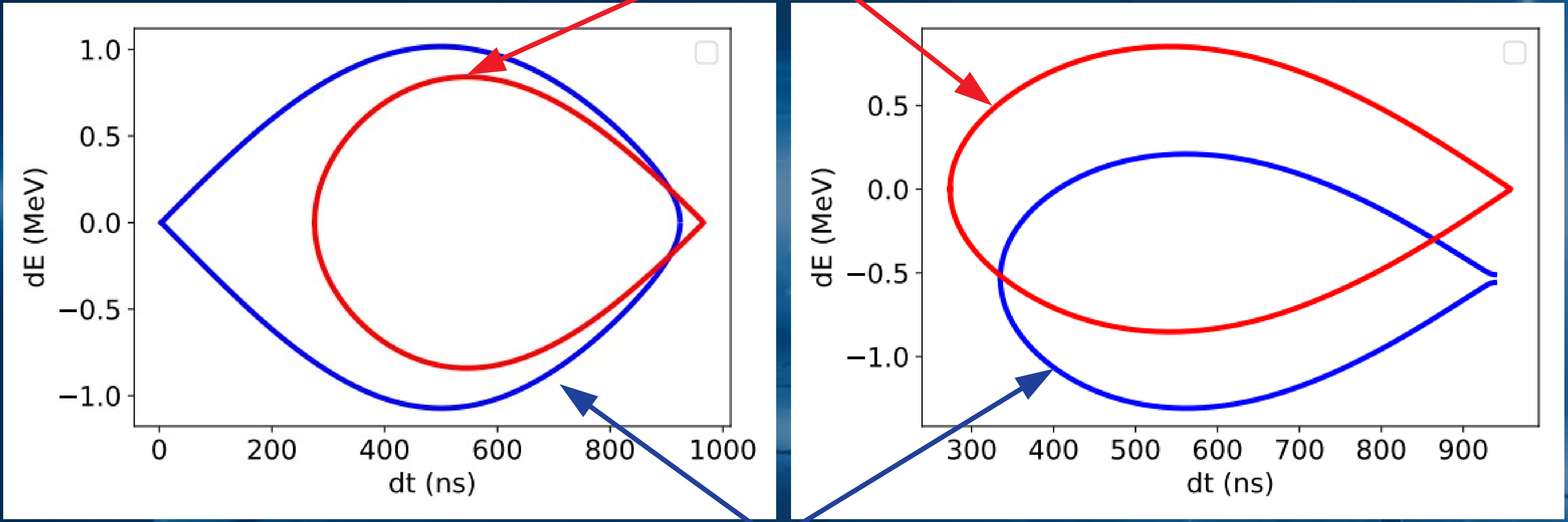


Separatrix

Expectation

Start of injection

During return to B-Train

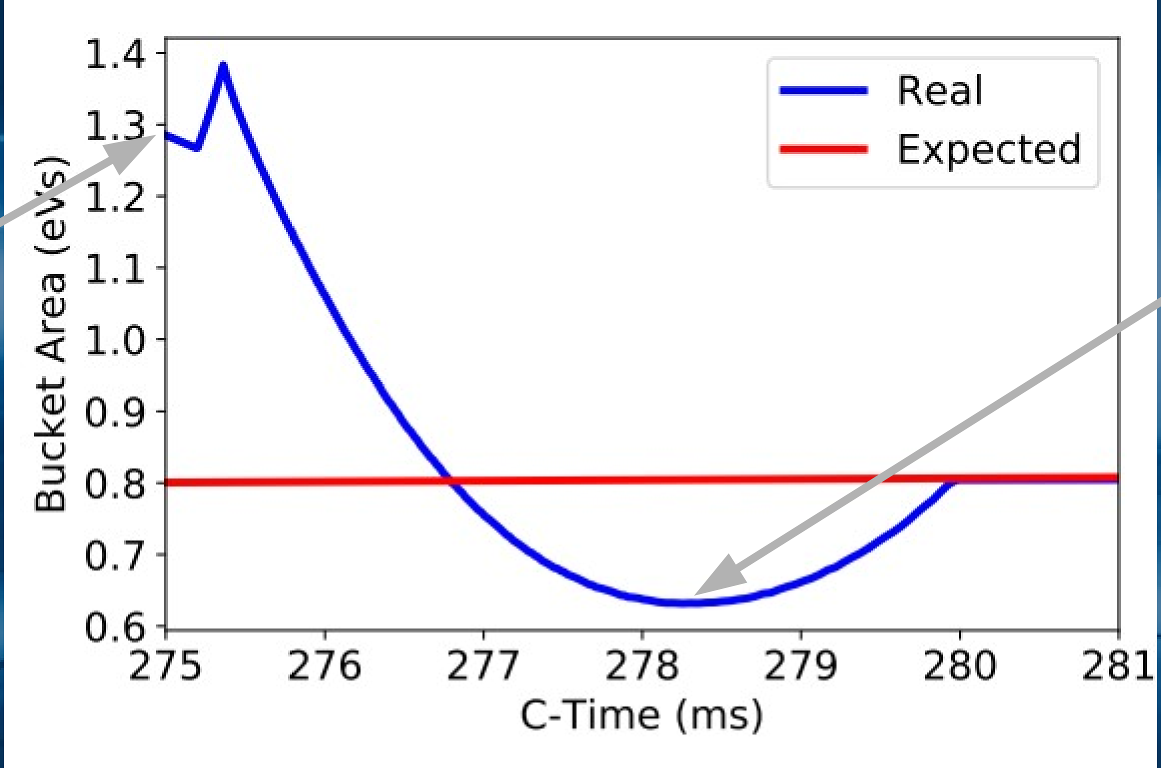


Reality

Injection on the Ramp

Longitudinal Acceptance

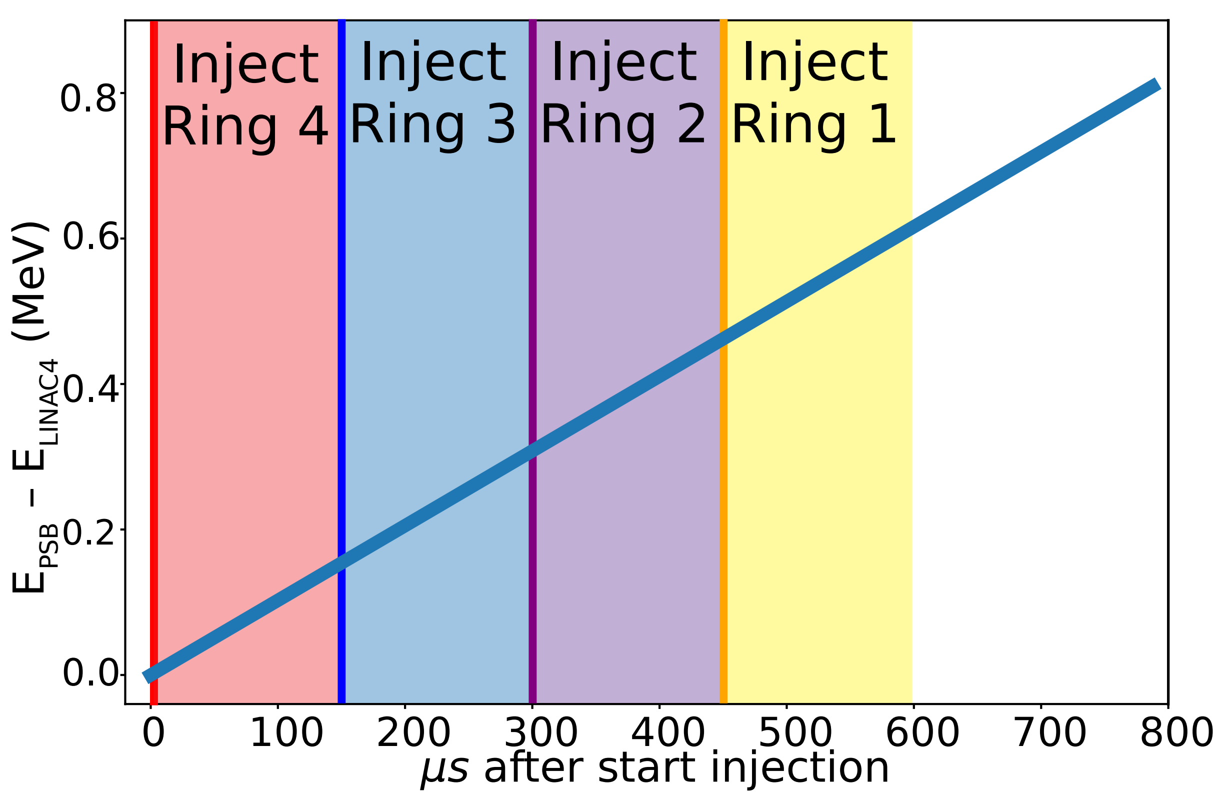
Large initial acceptance



Minimum acceptance during return to design frequency

Injection on the Ramp

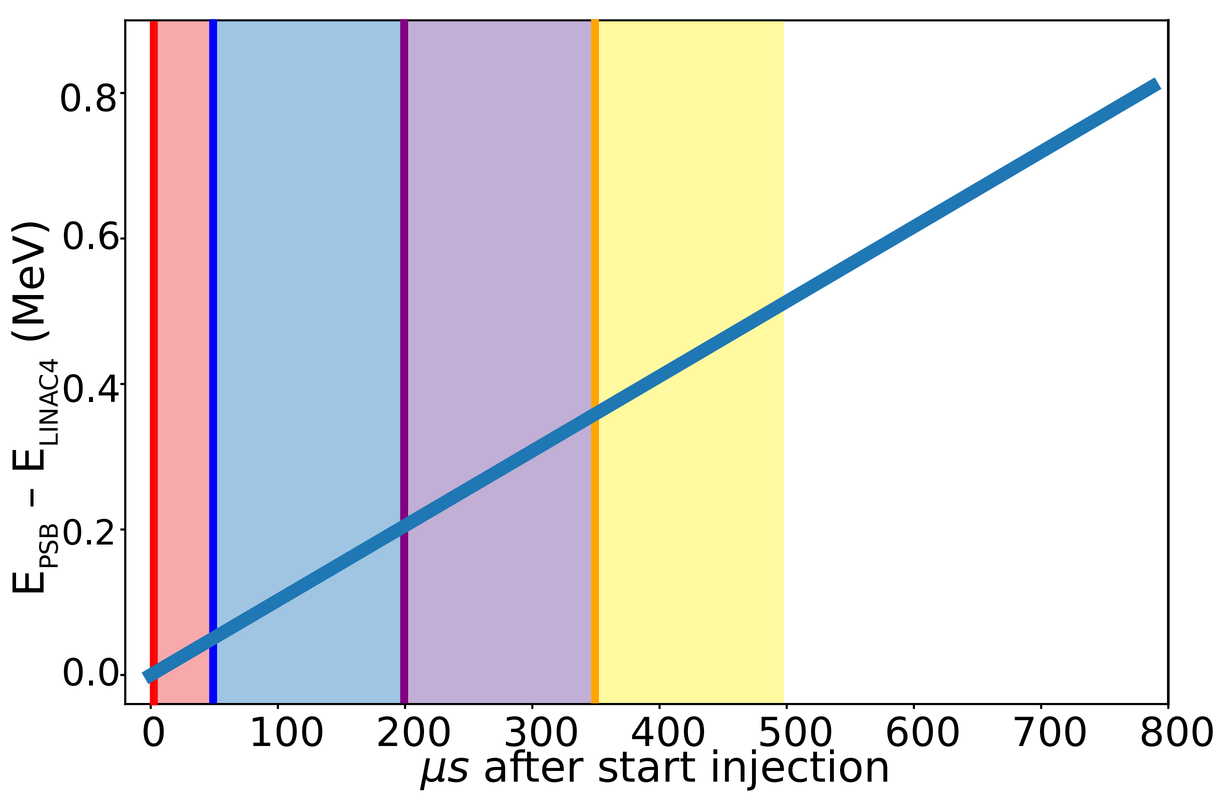
Energy Offset



- During injection the magnetic field is increasing, so the relative energy difference between the PSB and Linac4 increases
- As each ring starts injecting there will be an increasing energy difference between the design energy and the injection energy

Injection on the Ramp

Energy Offset



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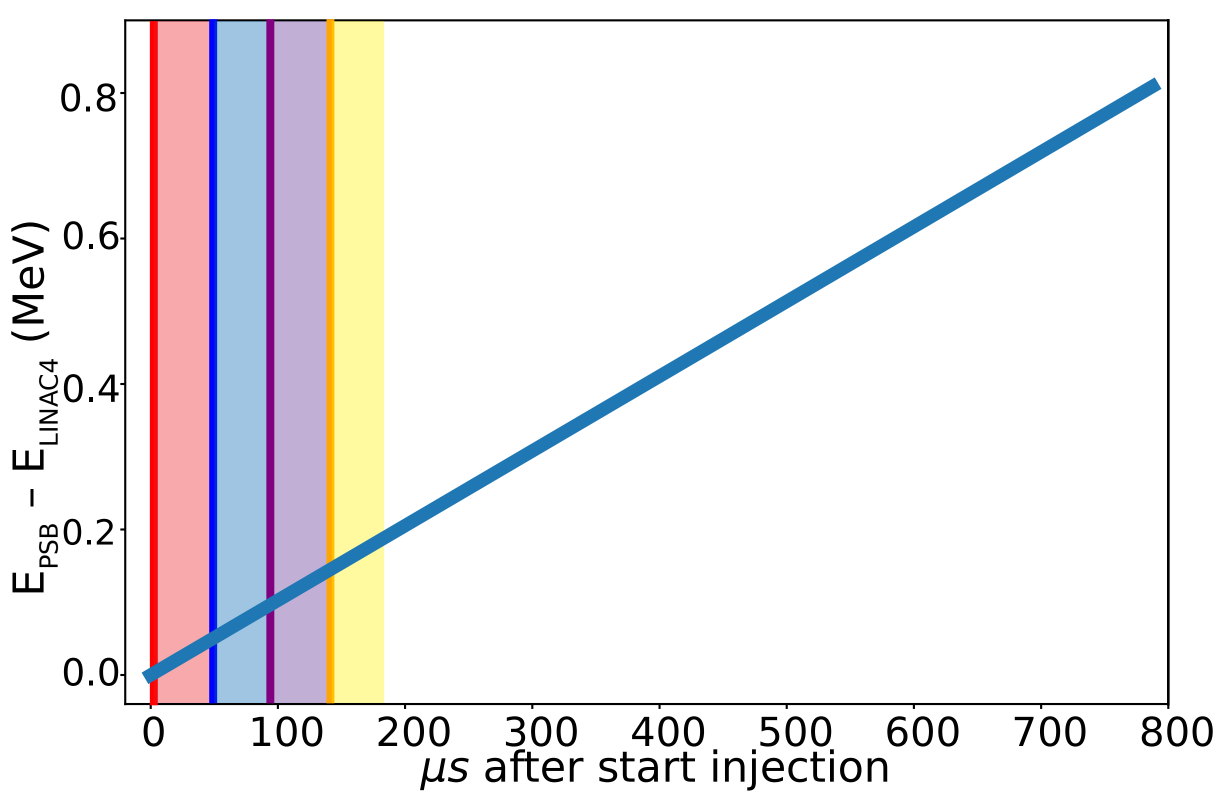
Injection on the Ramp

Energy Offset



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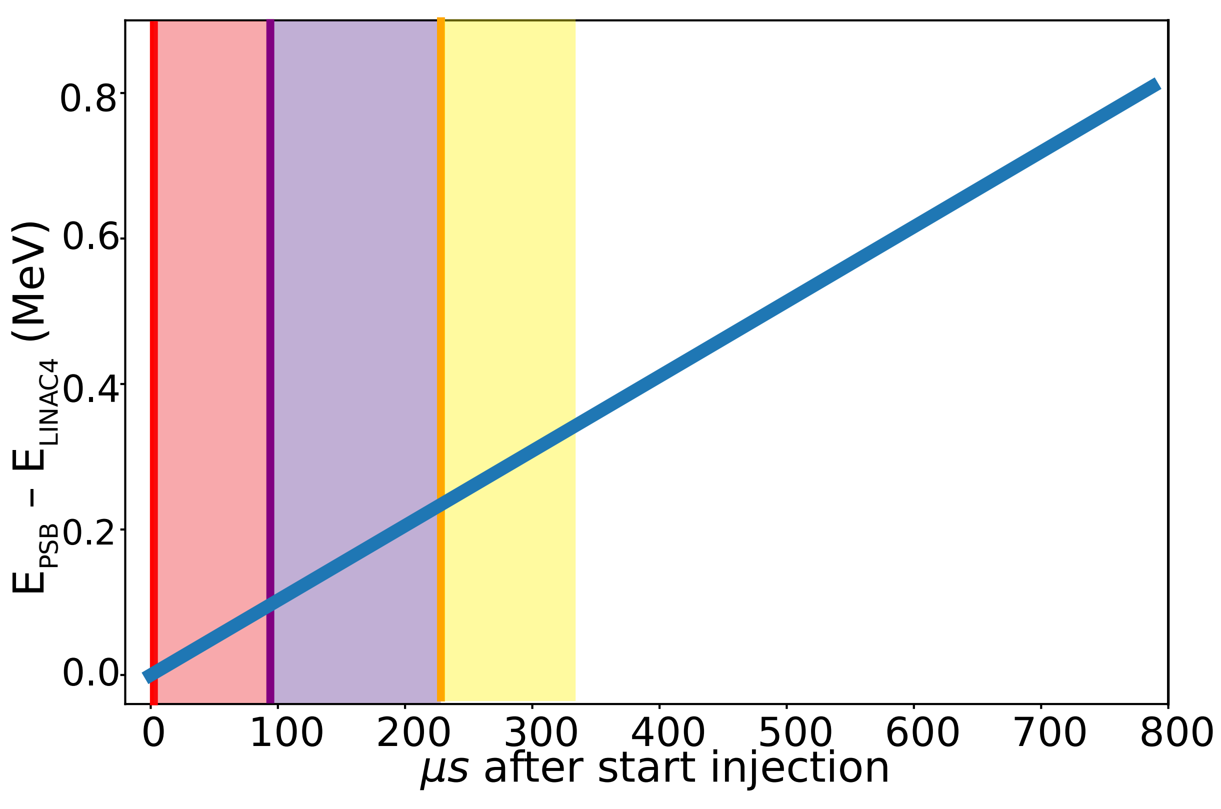
Injection on the Ramp
Energy Offset



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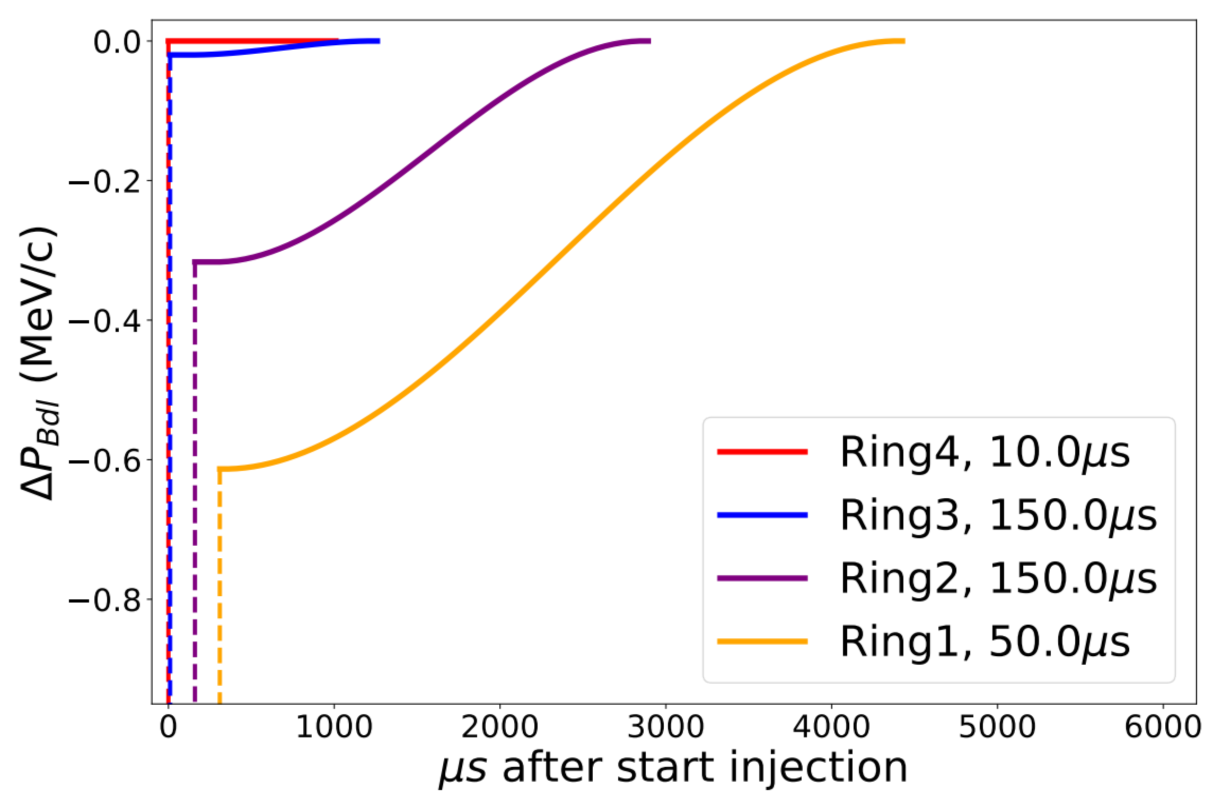
Injection on the Ramp

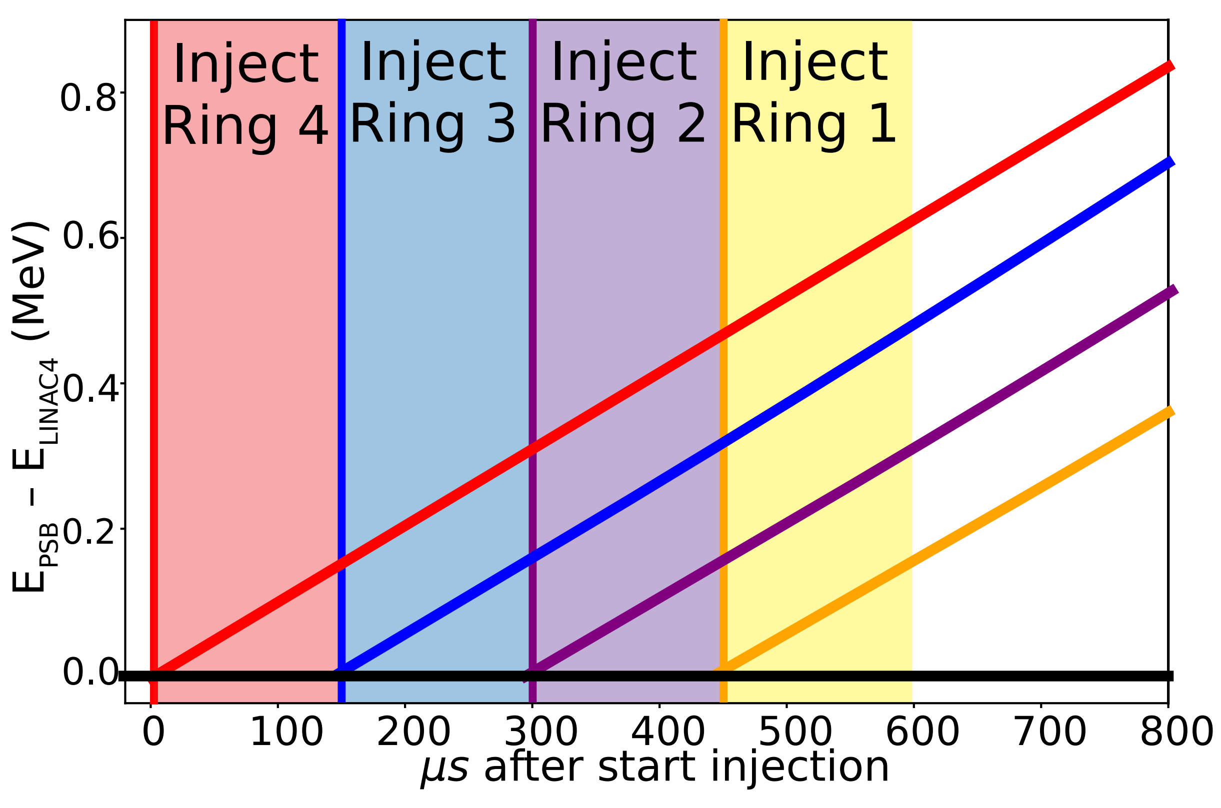
Energy Offset Compensation



- Special dipole “Bdl” trim circuits will offset the magnetic field at the start of injection to each ring

Injection on the Ramp

Energy Offset Compensation



- Special dipole “Bdl” trim circuits will offset the magnetic field at the start of injection to each ring
- With the trim field added, every ring will have the same energy offset relative to Linac4 during injection

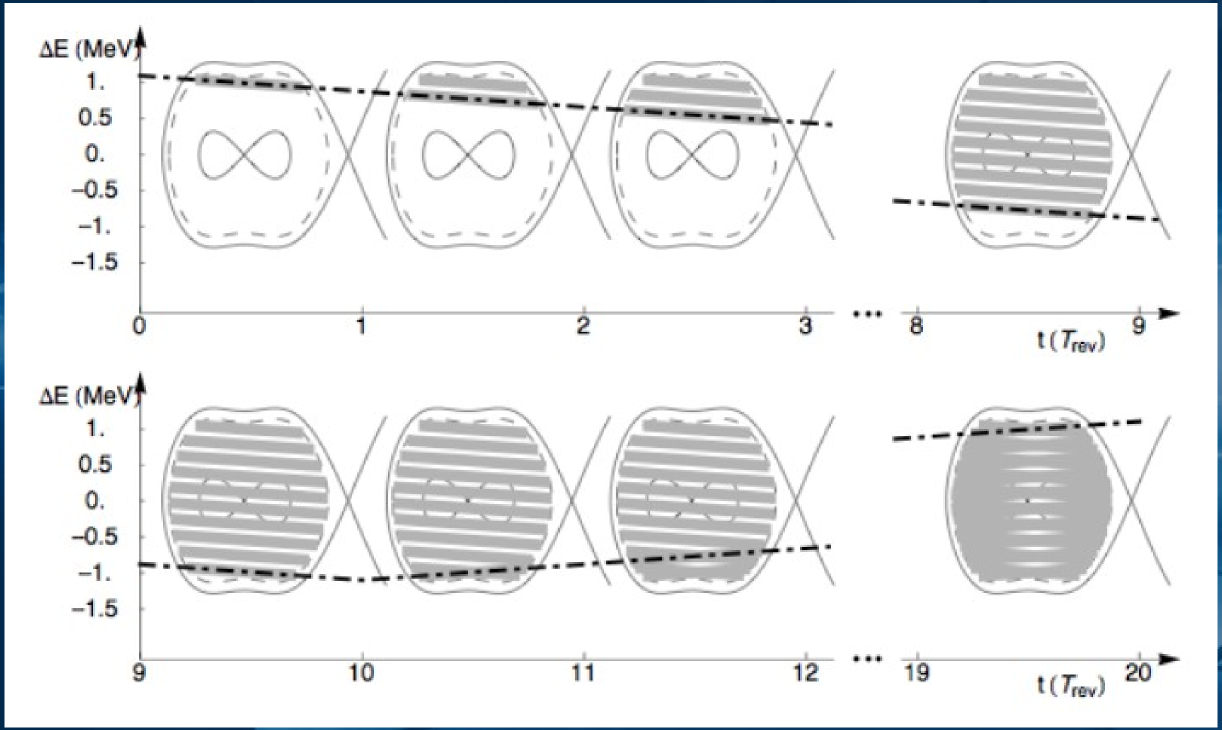
Injection On The Ramp

- The beam dynamics of injection on the ramp is complex
- Pre-LS2, a coasting beam was injected and captured, therefore an accurate description of the beam dynamics was less important
- Injecting directly into the bucket with Linac4, and preserving the beam quality, will require very accurate knowledge of the beam dynamics
- Due to the complexity of injecting on the ramp (not just longitudinally) we will restart with a flat bottom, and investigate injection on the ramp as an optimisation later

Longitudinal Painting

Longitudinal Painting

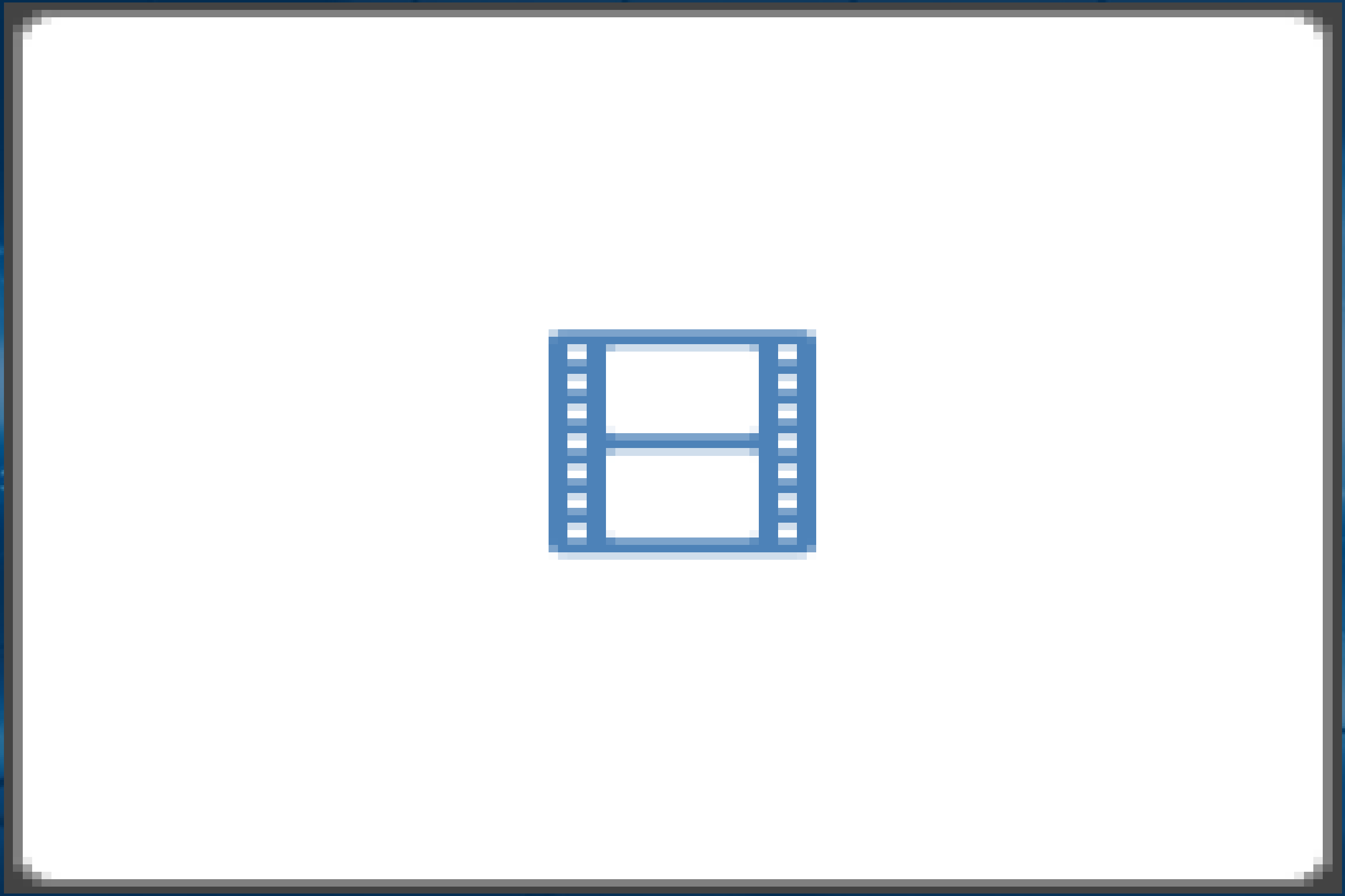
Principle



- Longitudinal painting will allow very precise and uniform filling of the bucket, giving higher quality beams
- First described by C. Carli and R. Garoby in 2008 (AB-Note-2008-011 ABP)
- Linac4 mean energy is modulated to the limits of a target contour
- The chopping factor is modulated to match the length of the contour at that energy

Longitudinal Painting

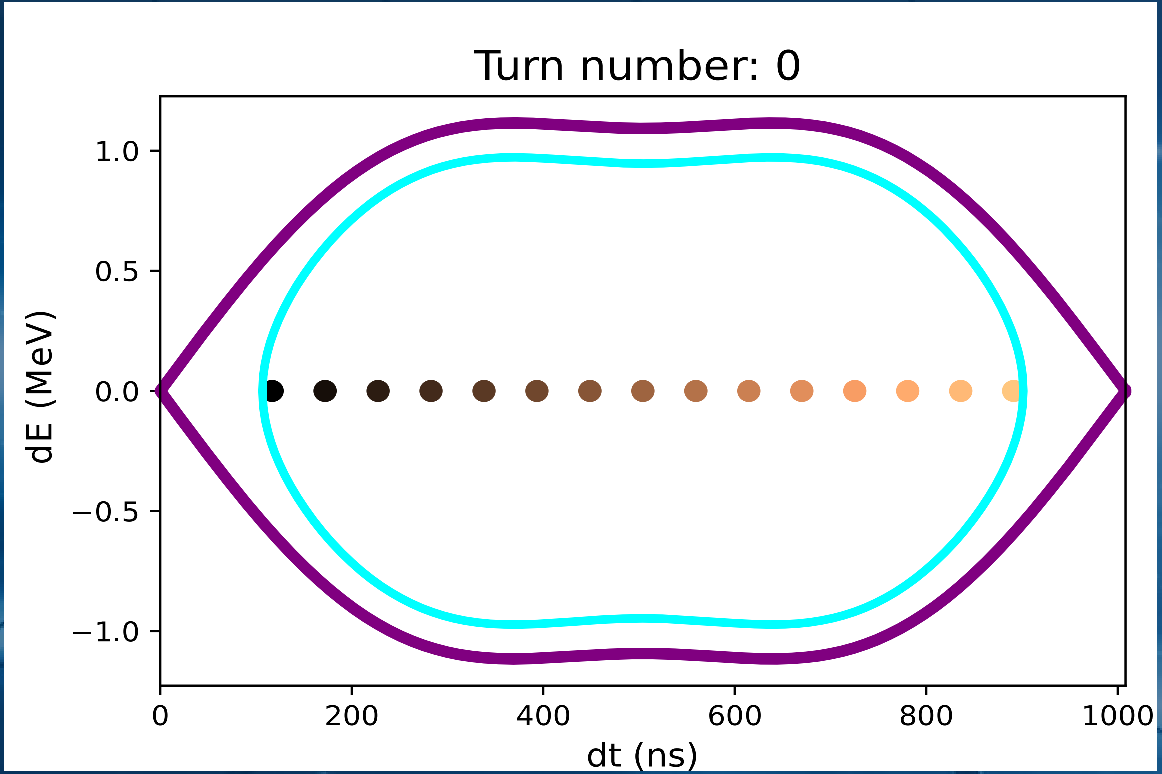
Principle



Longitudinal Painting

Synchrotron Motion

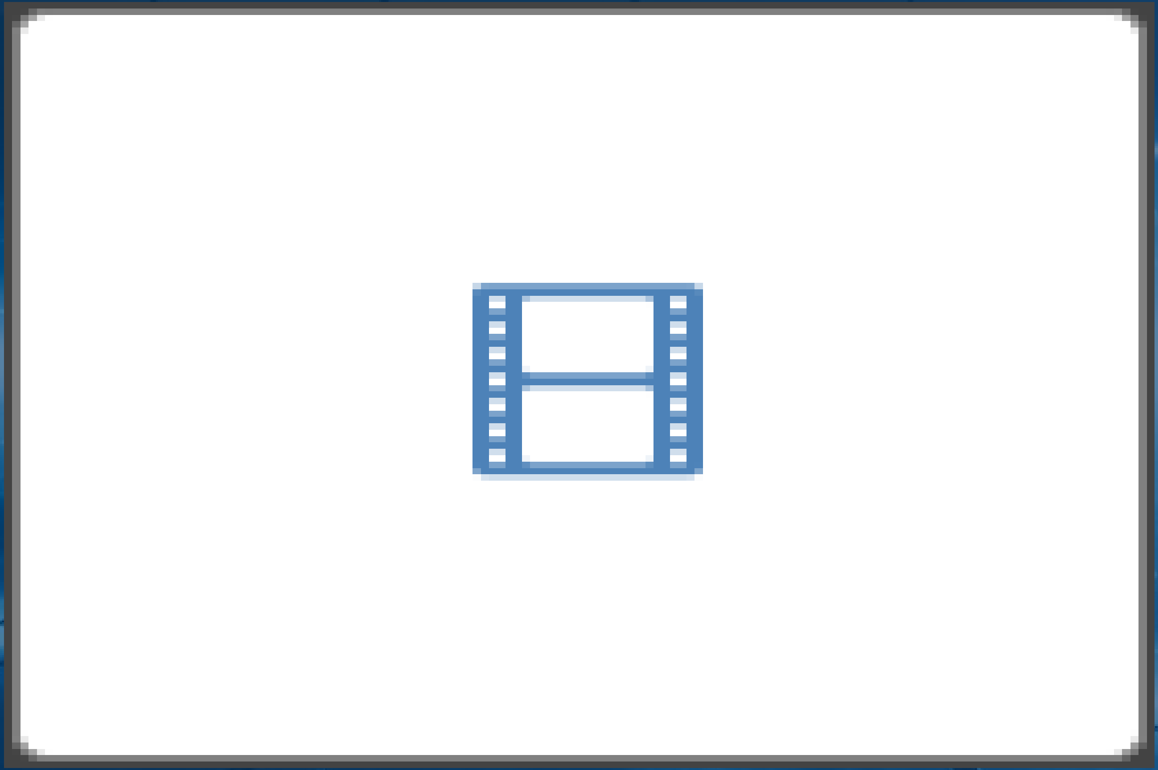
- Line of test particles placed along the middle of the bucket



Longitudinal Painting

Synchrotron Motion

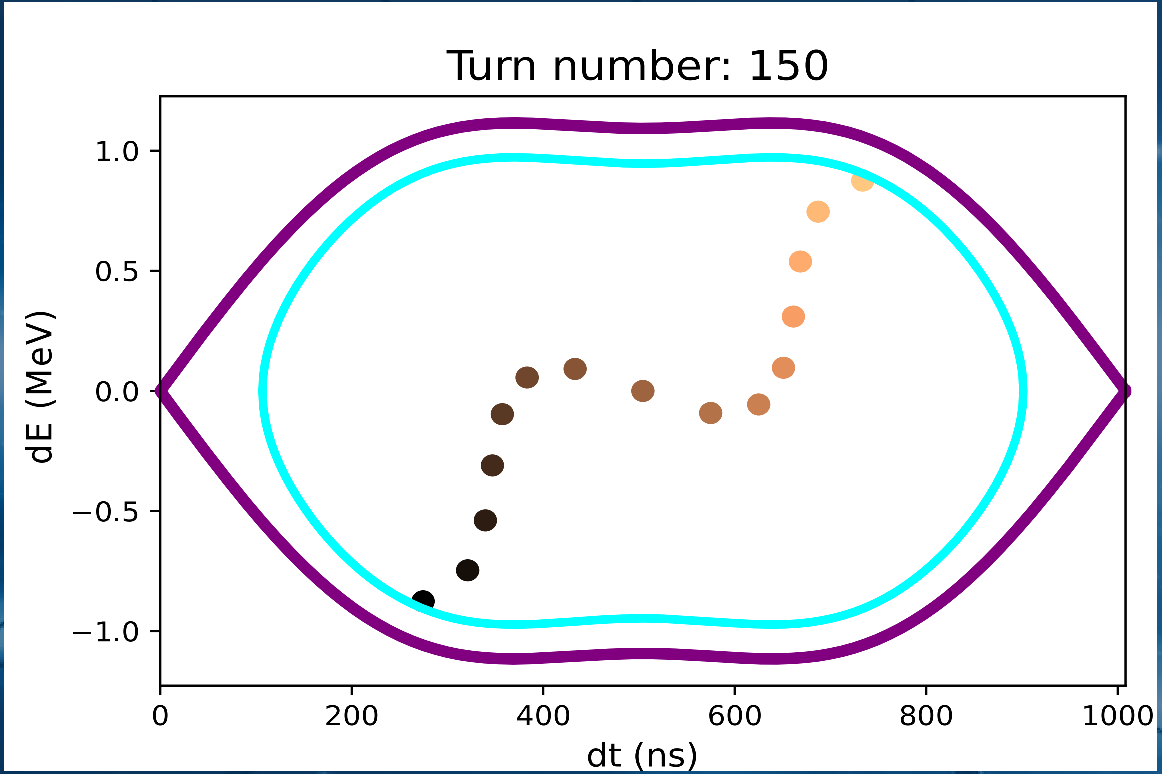
- Line of test particles placed along the middle of the bucket
- Track for 150 turns (maximum duration of injection)



Longitudinal Painting

Synchrotron Motion

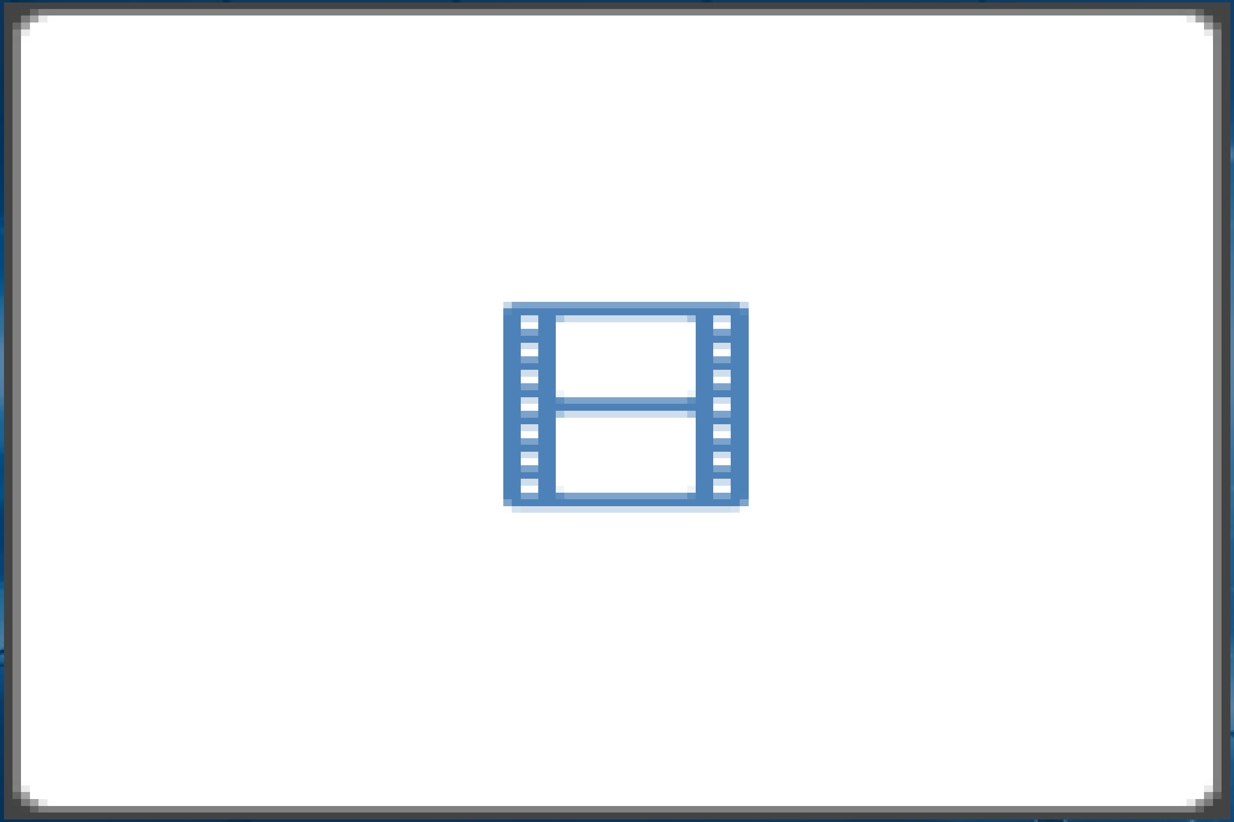
- Line of test particles placed along the middle of the bucket
- Track for 150 turns (maximum duration of injection)
- Significant synchrotron motion despite short time



Longitudinal Painting

Synchrotron Motion

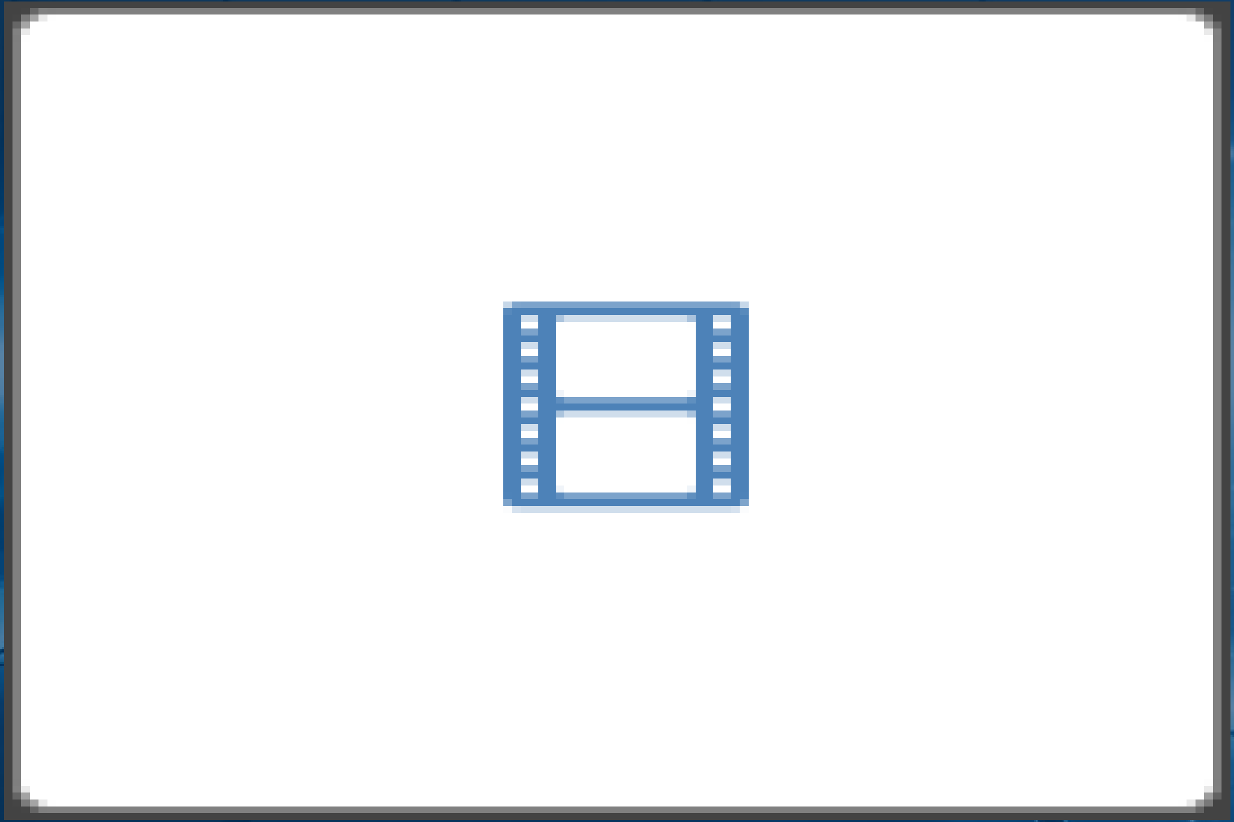
- 150 turns injected
- Every 7th injection shown
- Tracking **disabled**



Longitudinal Painting

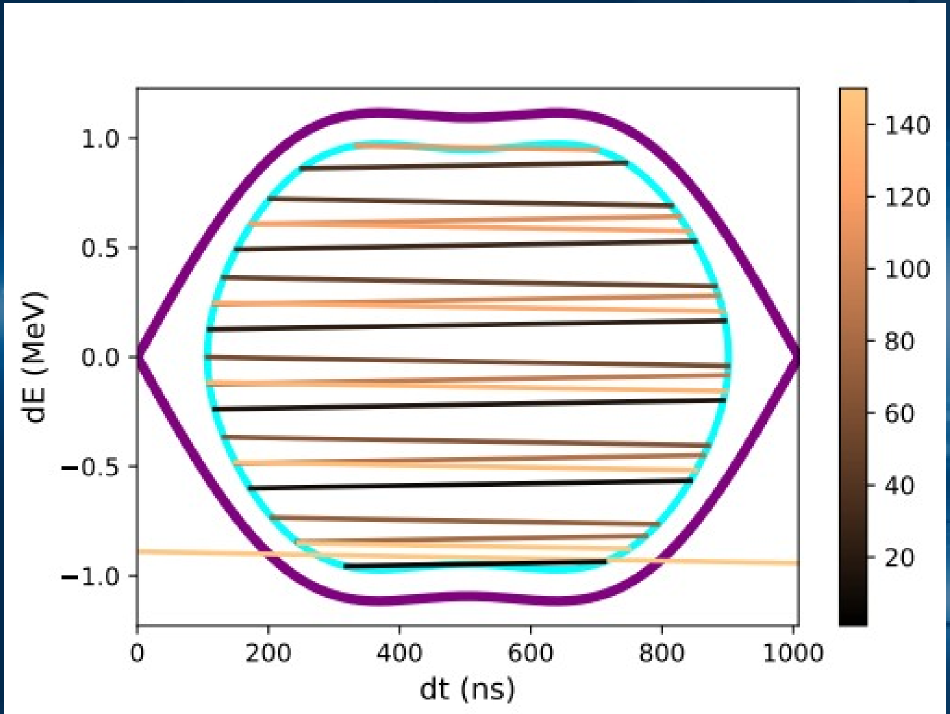
Synchrotron Motion

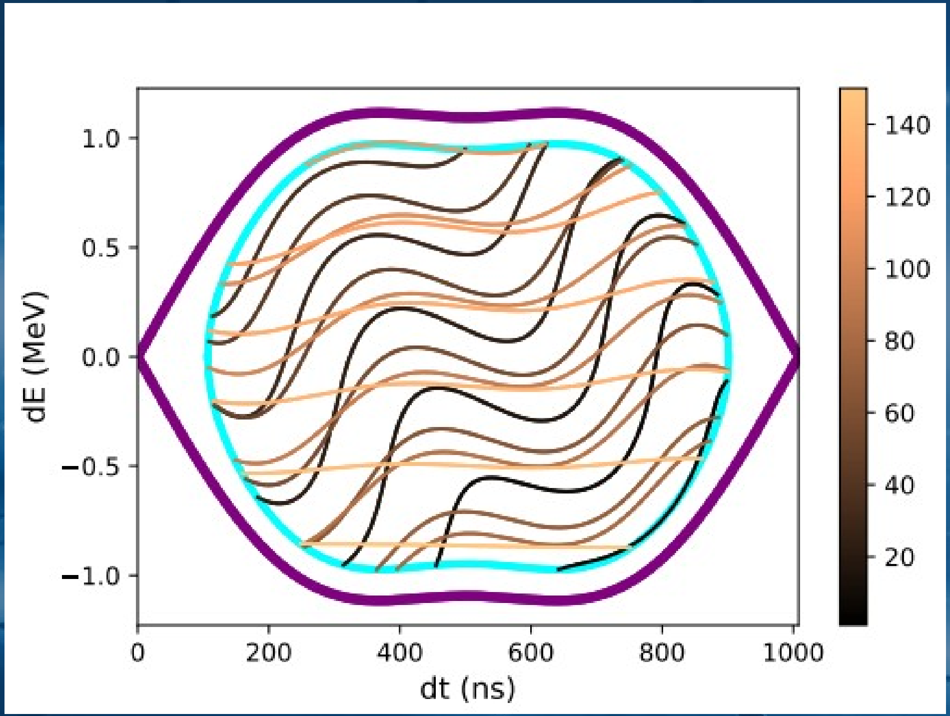
- 150 turns injected
- Every 7^{th} injection shown
- Tracking **enabled**



Longitudinal Painting

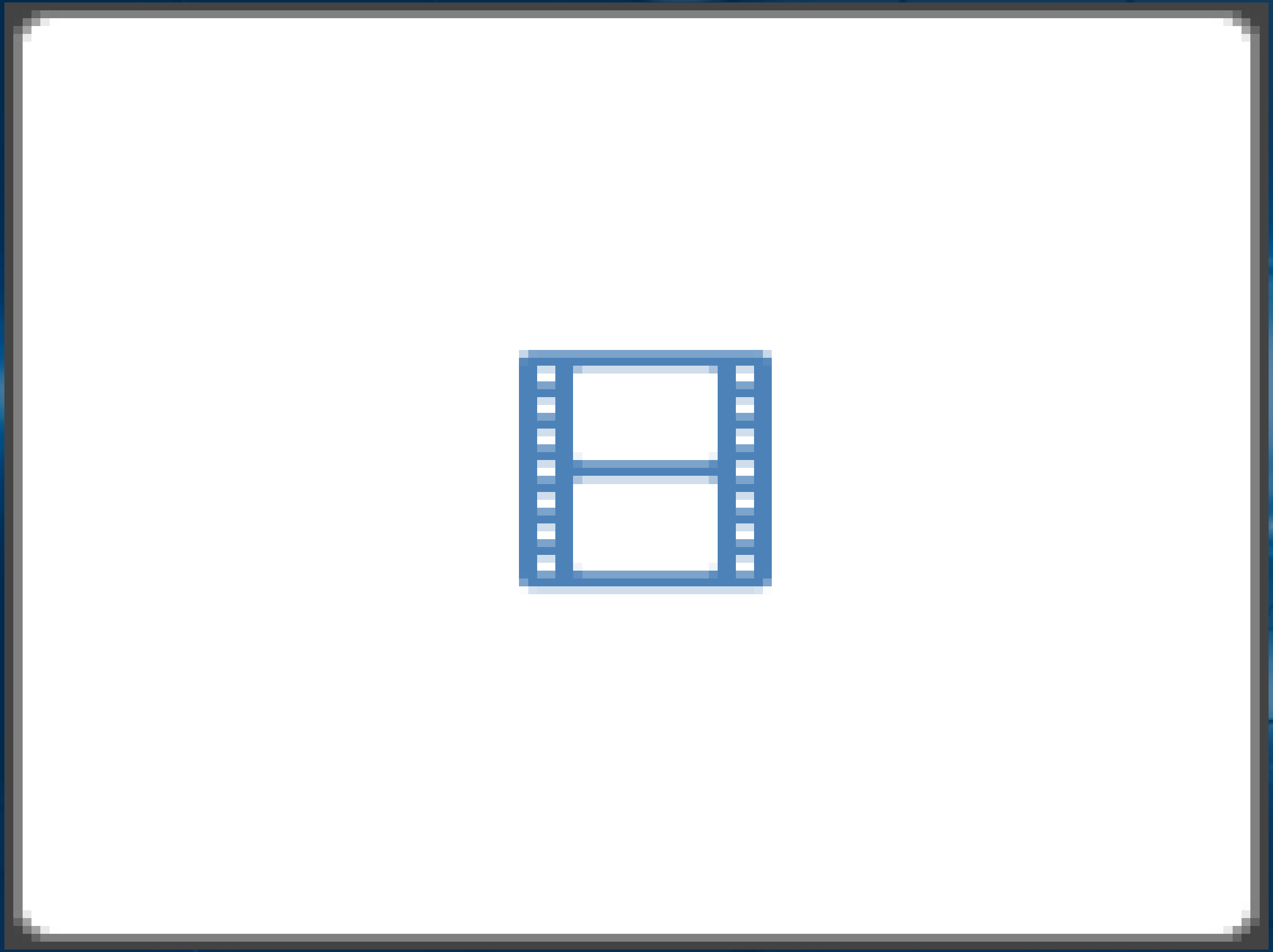
Synchrotron Motion





Longitudinal Painting

Tracking

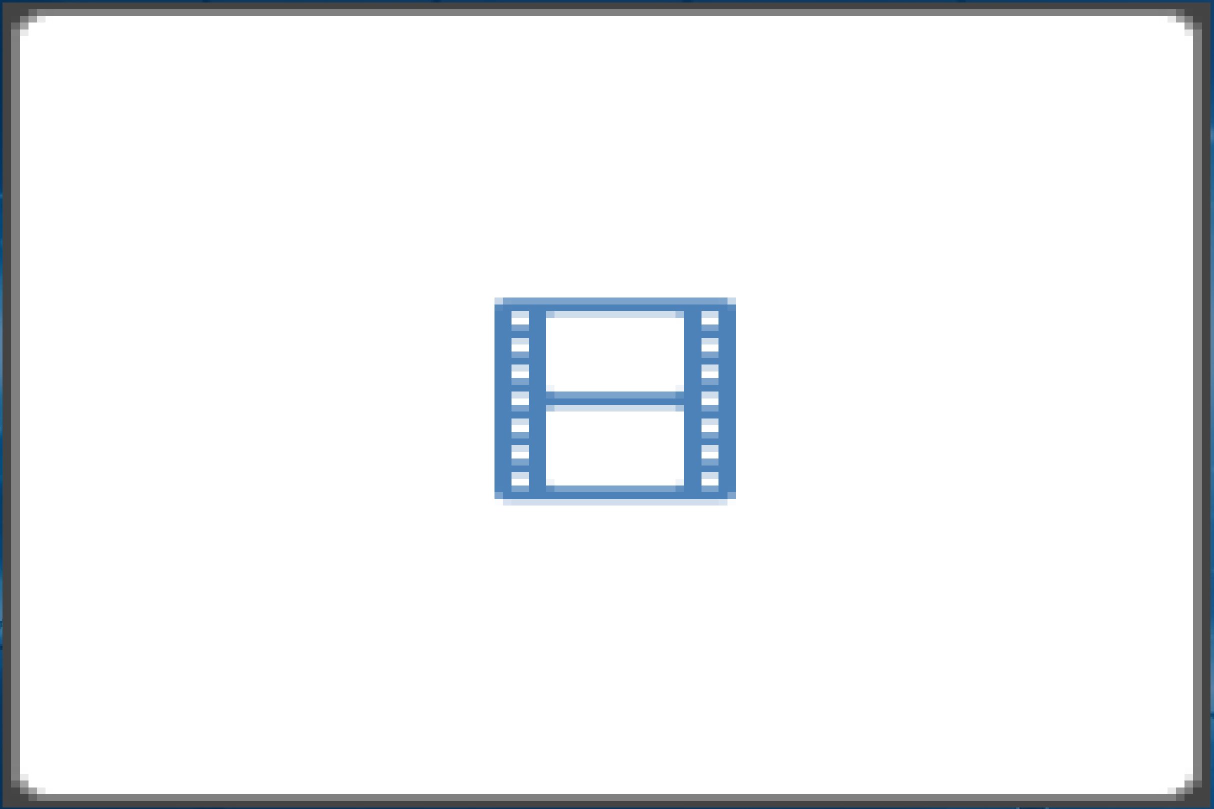


- The real beam has an energy spread
- The beam will not match the target if the spread isn't considered
- Significant beam loss may occur

Longitudinal Painting

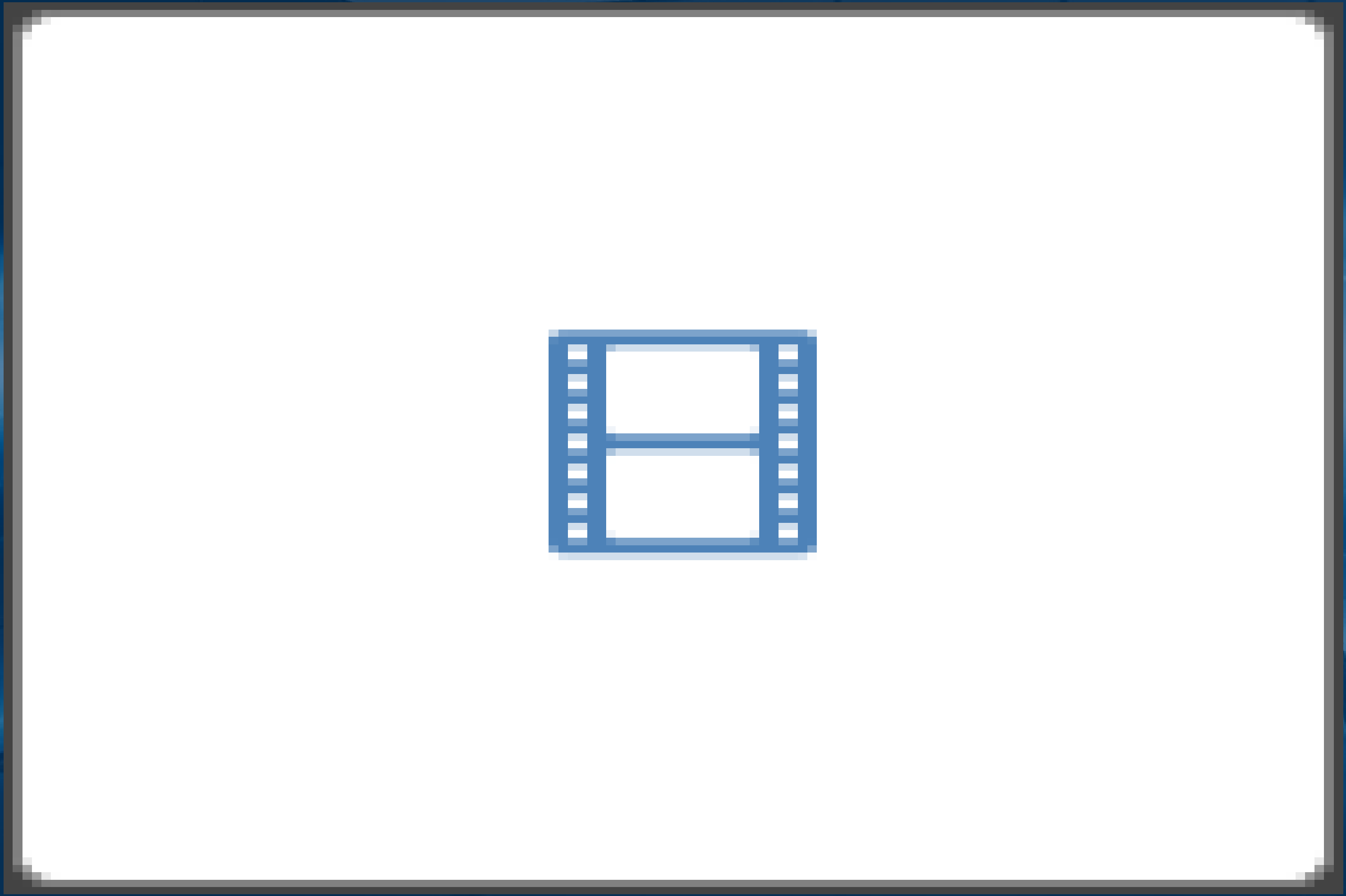
Effect of Linac4 Energy Spread

- The chopping pattern should be designed with the energy spread included
- A smaller energy modulation is needed to avoid wasting beam



Longitudinal Painting

Tracking 2



Conclusion

Conclusion

- RF phase noise will be used for controlled longitudinal emittance blow-up for most operational beams, with a new method for calculating the function
- Microwave instability driven by the impedance of the Finemet cavities is expected at high intensities, with a strong threshold dependence on the longitudinal distribution
- Voltage functions have been designed for each operational cycle, which take full advantage of the flexibility of the new Finemet RF systems and meet the beam dynamics constraints
- Post-LS2 the PSB will restart with injection on a flat-bottom, with injection on the ramp to be studied as an optimisation in the future
- In the long term, longitudinal painting has the potential to further improve beam performance and will be studied in more detail