Injection Studies for the ISIS Pre-Injector Upgrade

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Overview

01 Current ISIS Injection

02 Pre-Injector Upgrade Project

03 RF Programme Design

04 Working Point Optimisation

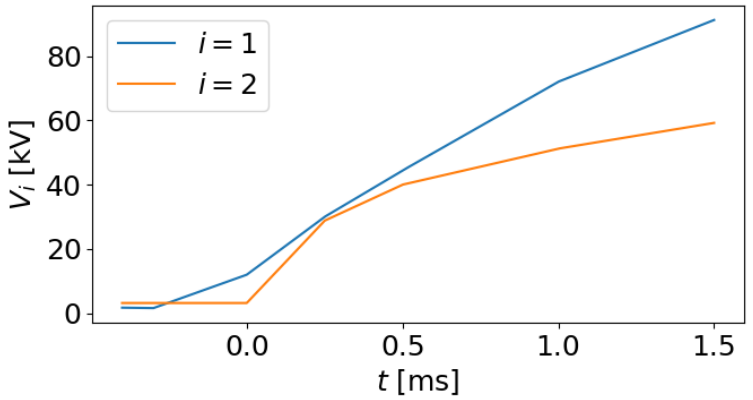
05 Stability Study

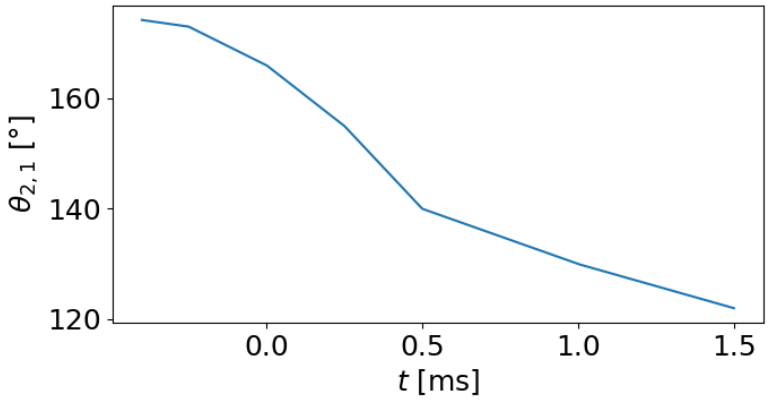
06 Longitudinal Painting Studies

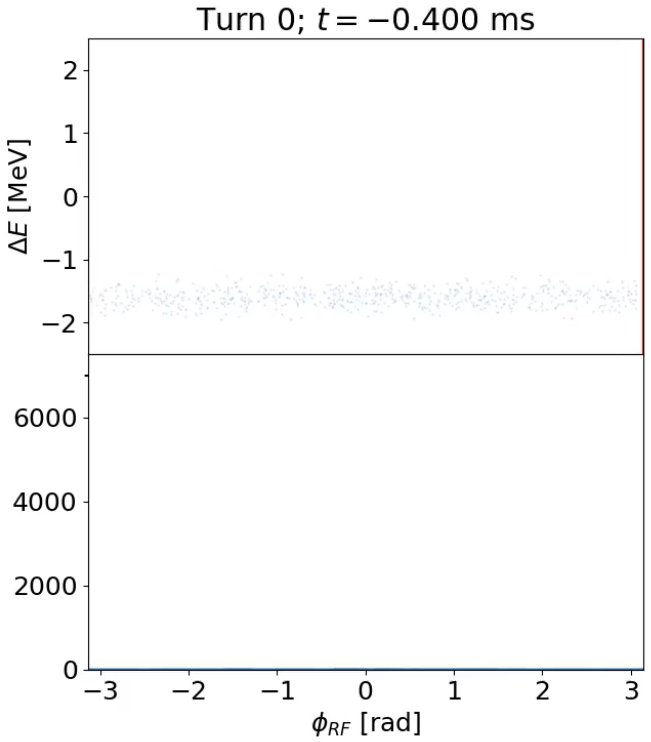
07 Summary

Current ISIS Injection

- Coasting beam injection (~200-300 μs)
  - 70 MeV H^- beam
  - 0.15% momentum spread
- Low initial ring RF voltage
- Flat RF frequency
- Falling main magnet field
  - Dispersive horizontal painting
- Voltage slowly increased for trapping
- Low energy trapping losses
  - 2-3% total injection + trapping
  - 0.5% from non-adiabatic capture
  - Acceptable but improvable
- AC-coupled BPMs:
  - No absolute measure of coasting beam position



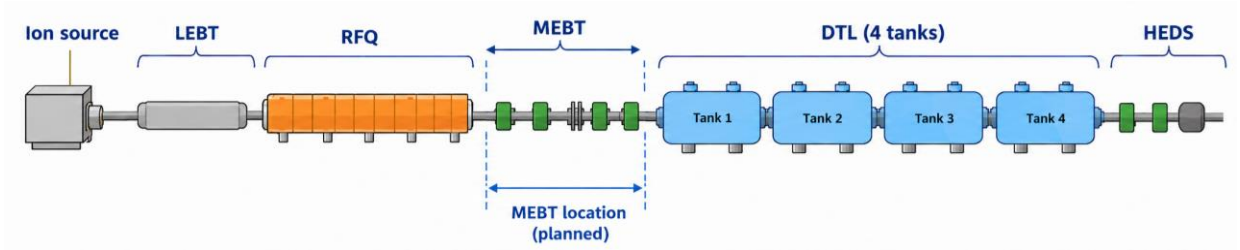




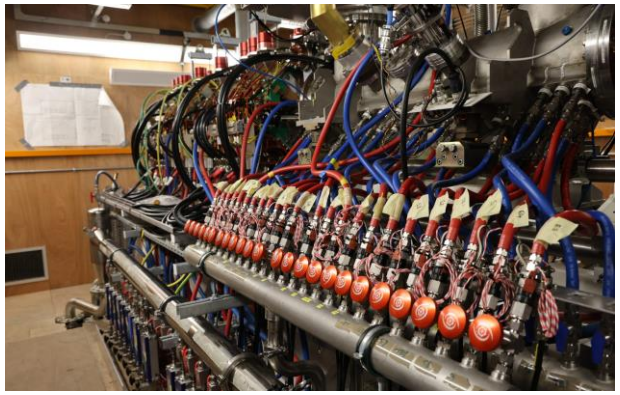
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ISIS Pre-Injector Upgrade Project

- Three pillars of project:
  - RF H^- ion source.
    - Increased reliability
    - Better maintainability
    - Longer operational lifetime
  - Medium-Energy Beam Transport (MEBT)
    - 6-dimensional matching (q-poles and QWRs)
    - Additional trajectory correction
    - Additional diagnostics
  - Electrostatic Chopper
    - Installed in MEBT
    - Synchronised to RCS RF
    - Controlled low-energy losses (665 keV)
    - Potential to mitigate transverse space charge effects







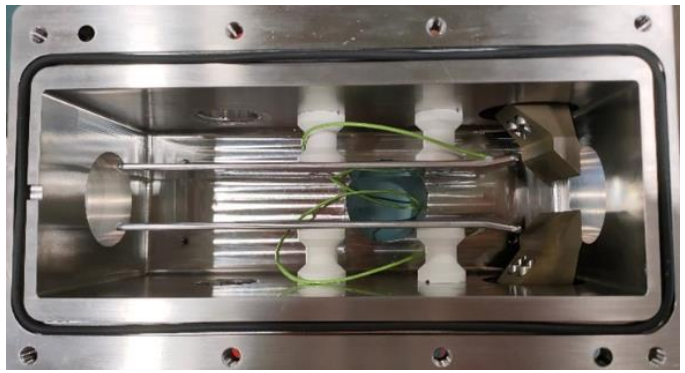


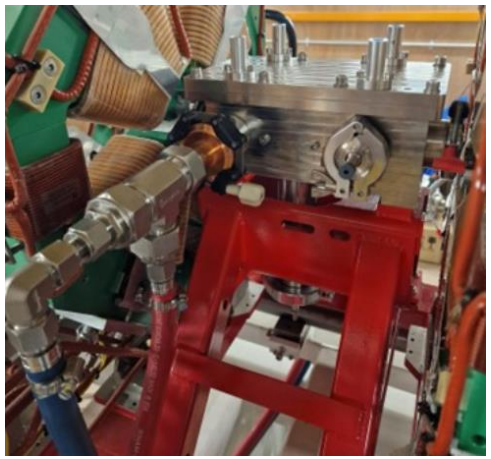


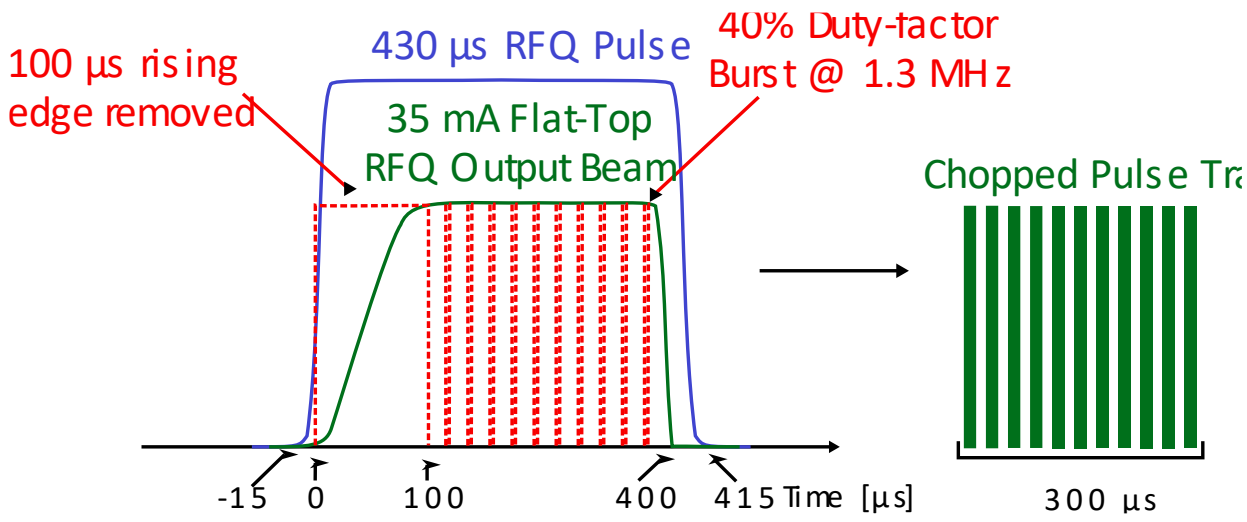
Images sourced from [1], [2]

MEBT Chopper

- 243 mm electrostatic chopper[3]
- Aluminium electrodes (±7.5 kV)
- Water-cooled tungsten beam dump
- Removes first 100 µs of the injector pulse train[4]
- Chops at ring RF frequency (1.34 MHz)
- Duty factor of up to 40%







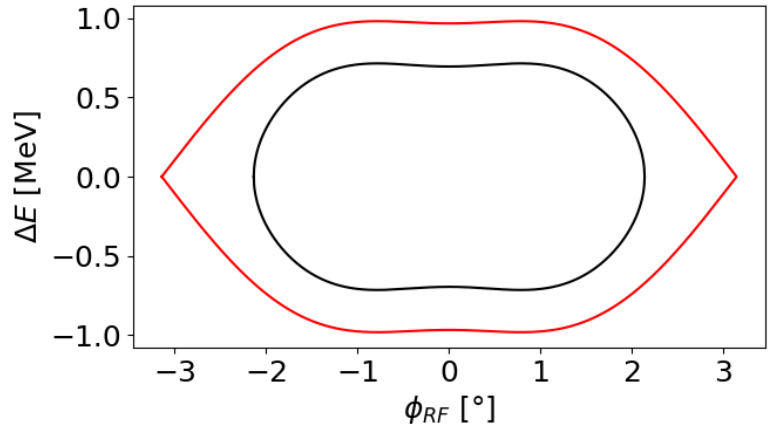
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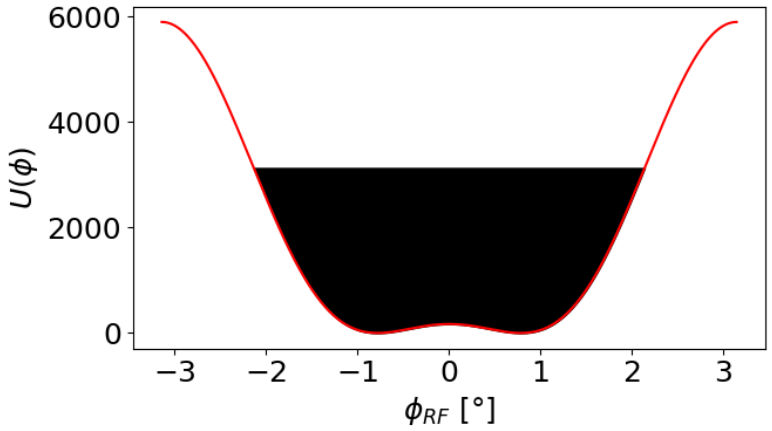
RF Voltage Programme

$$V(\phi) = \sum_{k=1}^{n} V_k \sin\left(\frac{h_k}{h_1}\phi + \theta_{k,1}\right) = V_1 \sin(\phi) + V_2 \sin(2\phi + \theta)$$

$$\left|\frac{Z_{\parallel}}{n}\right| \leq \frac{2\pi\beta^2 E\sigma_{\delta}^2|\eta|F}{e\hat{I}} \quad [5]$$

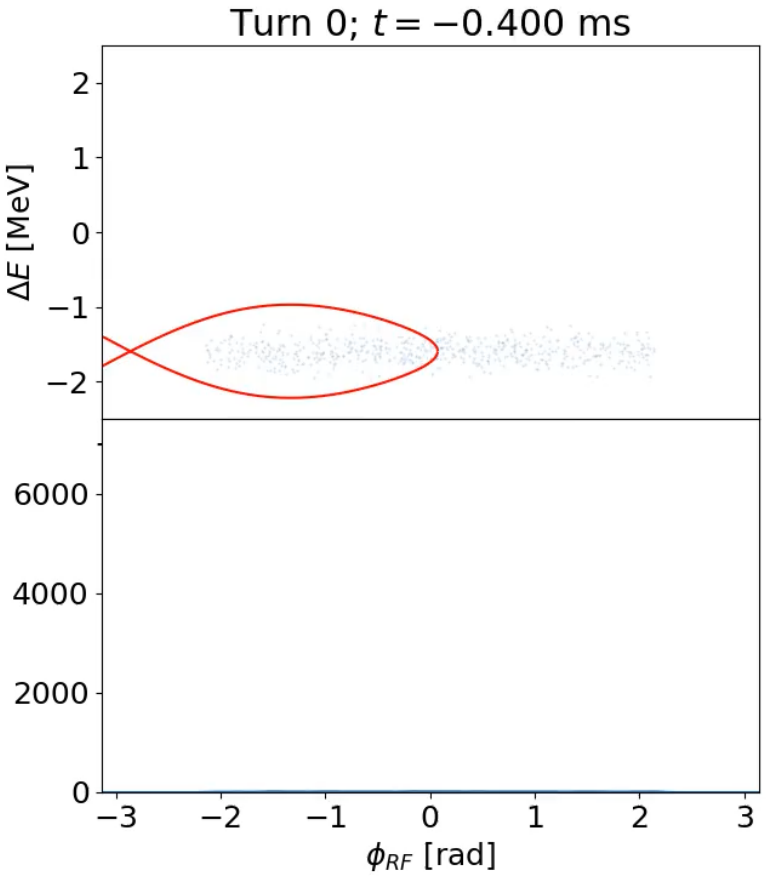
- Chopping requires bucket to chop into!
- Fixed RF frequency
- Need to:
  - Maximise bunching factor, $B = \frac{\langle I \rangle}{\hat{I}}$
  - Accept full momentum spread
  - Minimise longitudinal emittance
  - Stay below microwave instability threshold
- Choose $\theta = \pi$ to keep bucket symmetric
- Bunching factor solely function of harmonic ratio, $\delta = \frac{V_2}{V_1}$
- Fundamental voltage chosen to satisfy other criteria

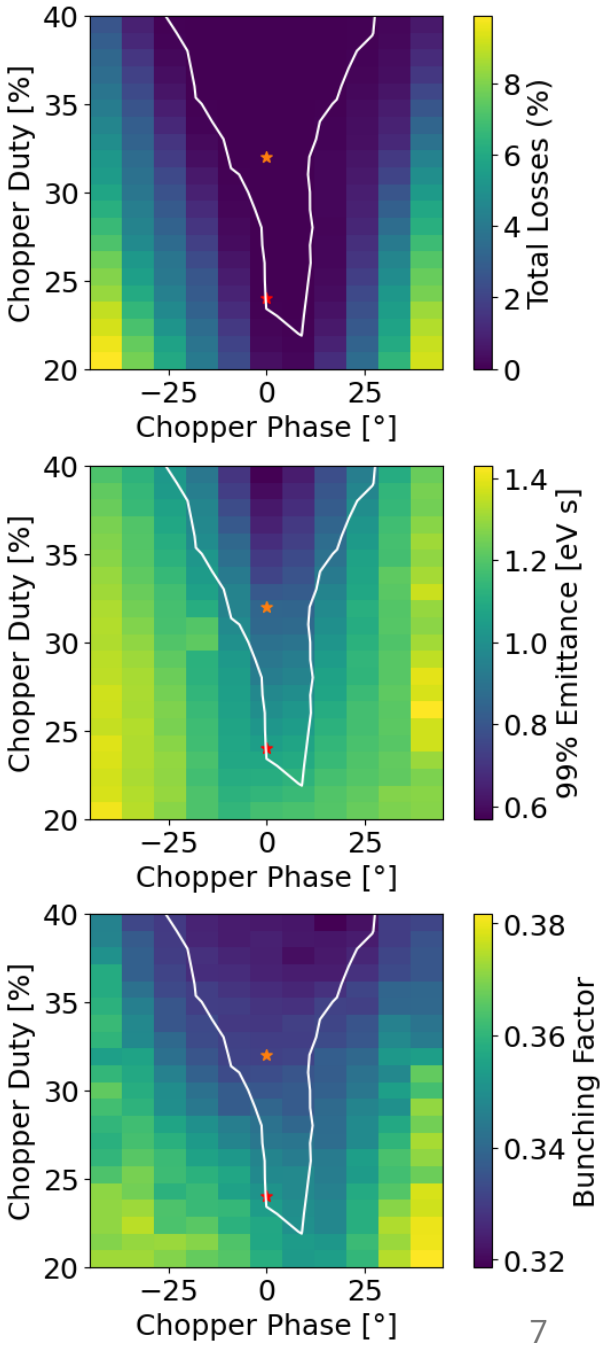




Chopper Working Point Optimisation

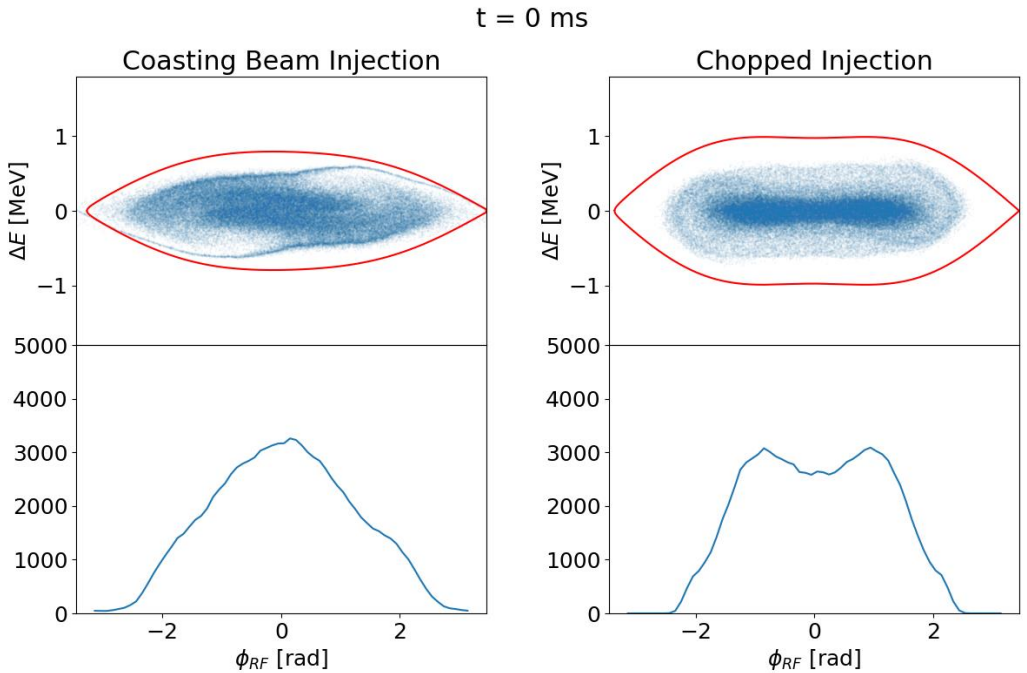
- Need to determine working point of chopper
- Goal intensity: 300 μA
- Assume
  - 35 mA @ RFQ exit
  - Perfect transmission through DTL
- Scan chopper phase and duty factor
- Optimisation criteria:
  1. 0% loss
  2. Maximised bunching factor
  3. Minimised longitudinal emittance
- Iterative process with voltage programme optimisation
- **WP found at 32% duty, 0° phase**



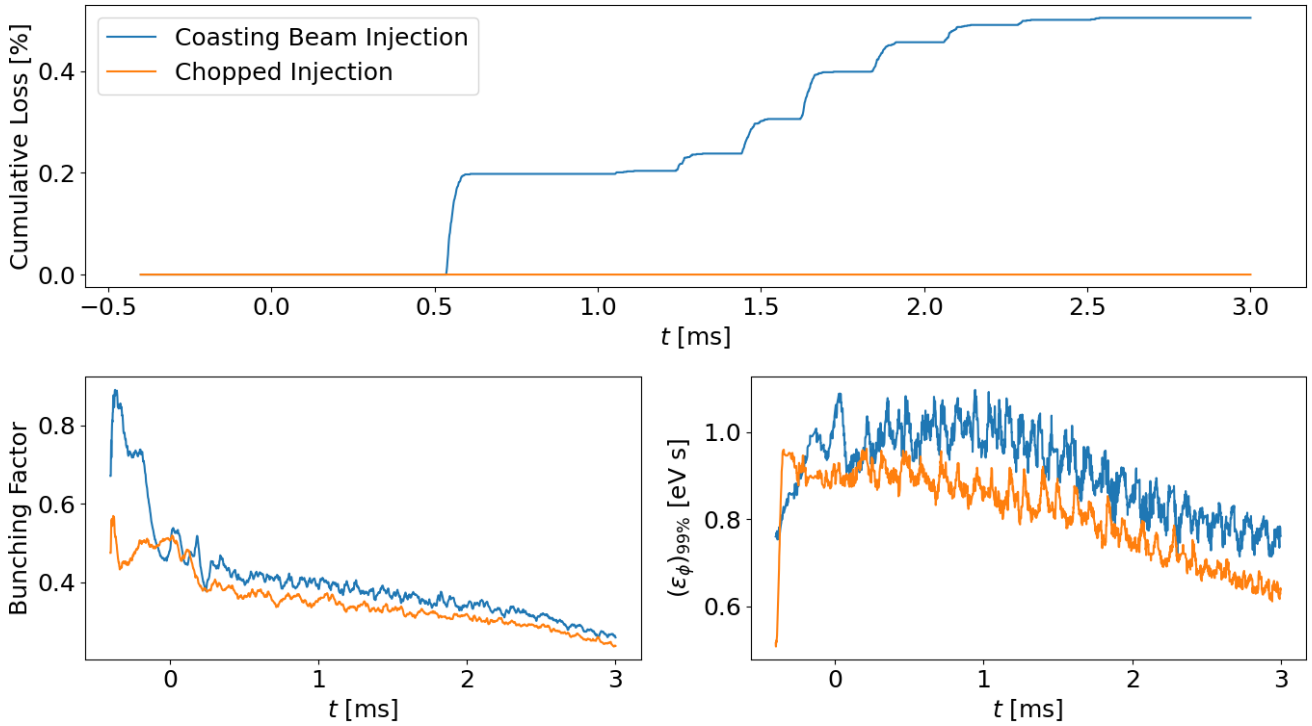


Comparison to Normal Operation

- Clear improvement on beam losses
- Small reduction in bunching factor as expected



- Good improvement (~15%) in 99% emittance
- Slight reduction in peak line density at low energies

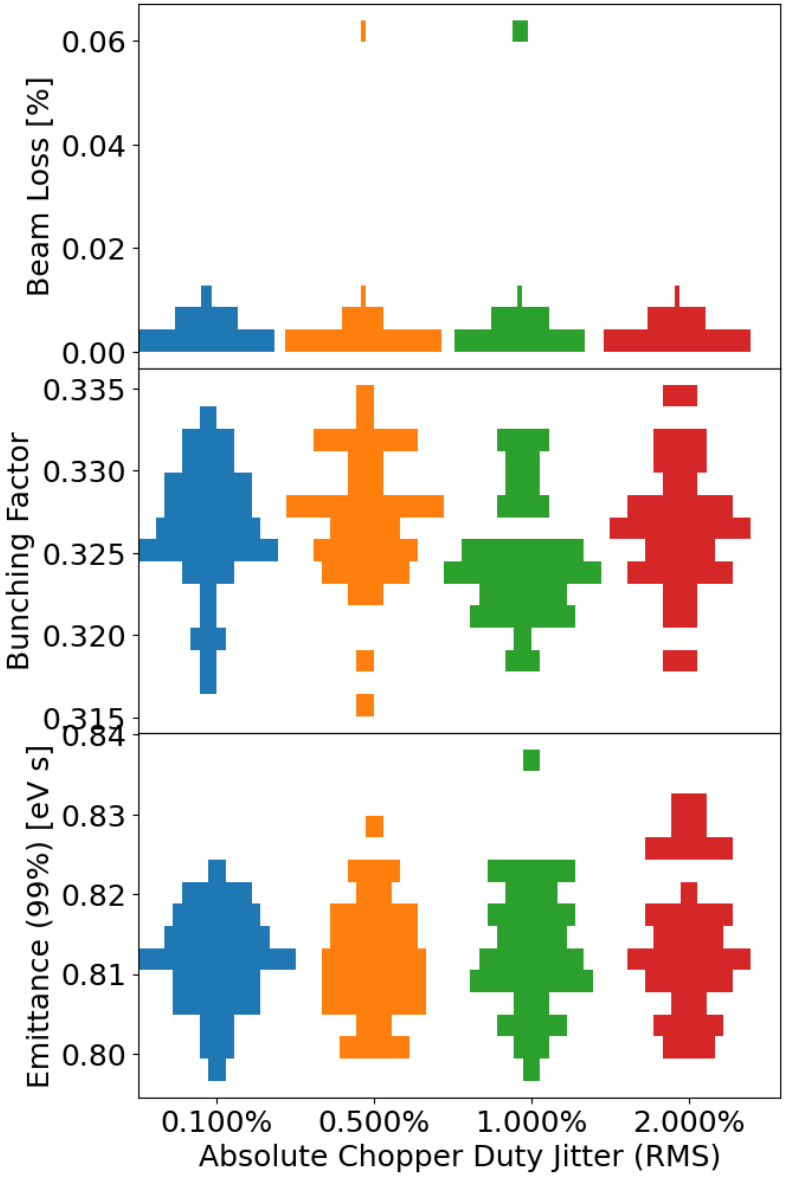


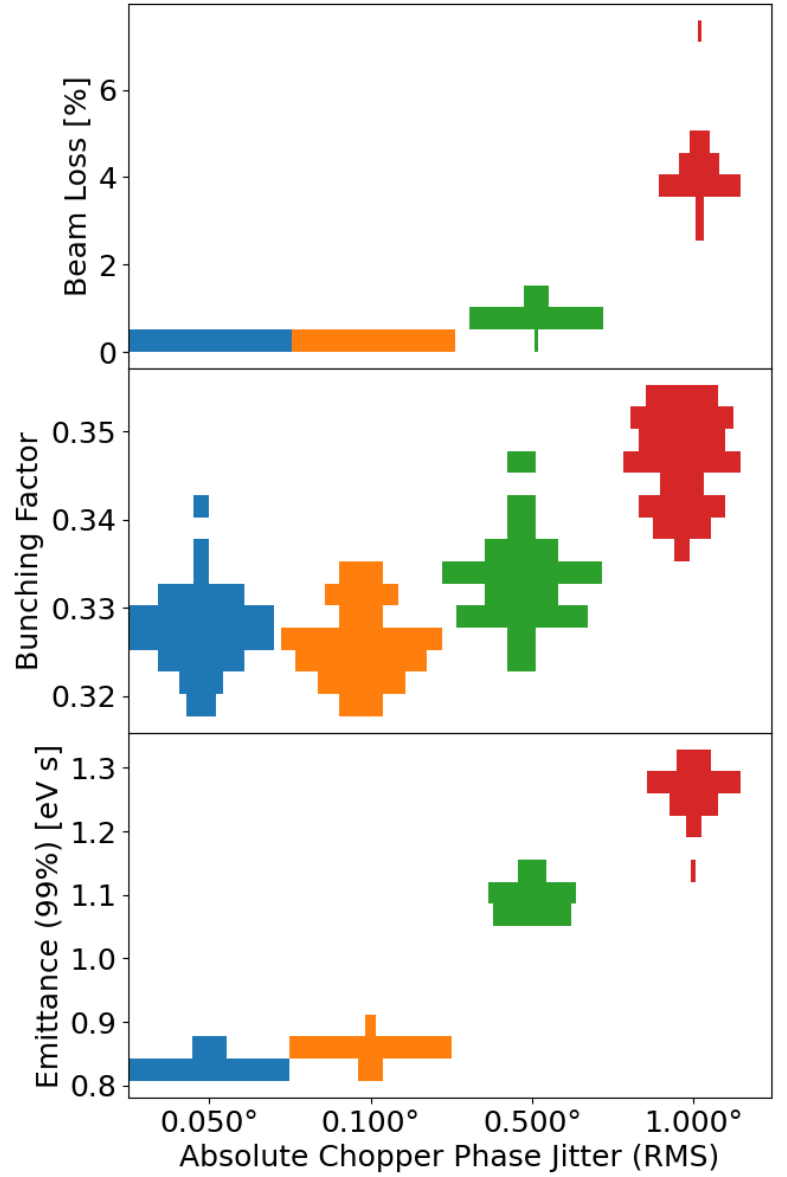
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Chopper Working Point Stability

- Need to define required chopper stability
- Apply gaussian noise to chopper demand
- Duty and phase noise investigated independently
- 40 repeats per noise level
- Much more sensitive to phasing jitter
  - Ideally < 0.05° (RMS)
- Duty factor jitter < 0.5% (RMS)



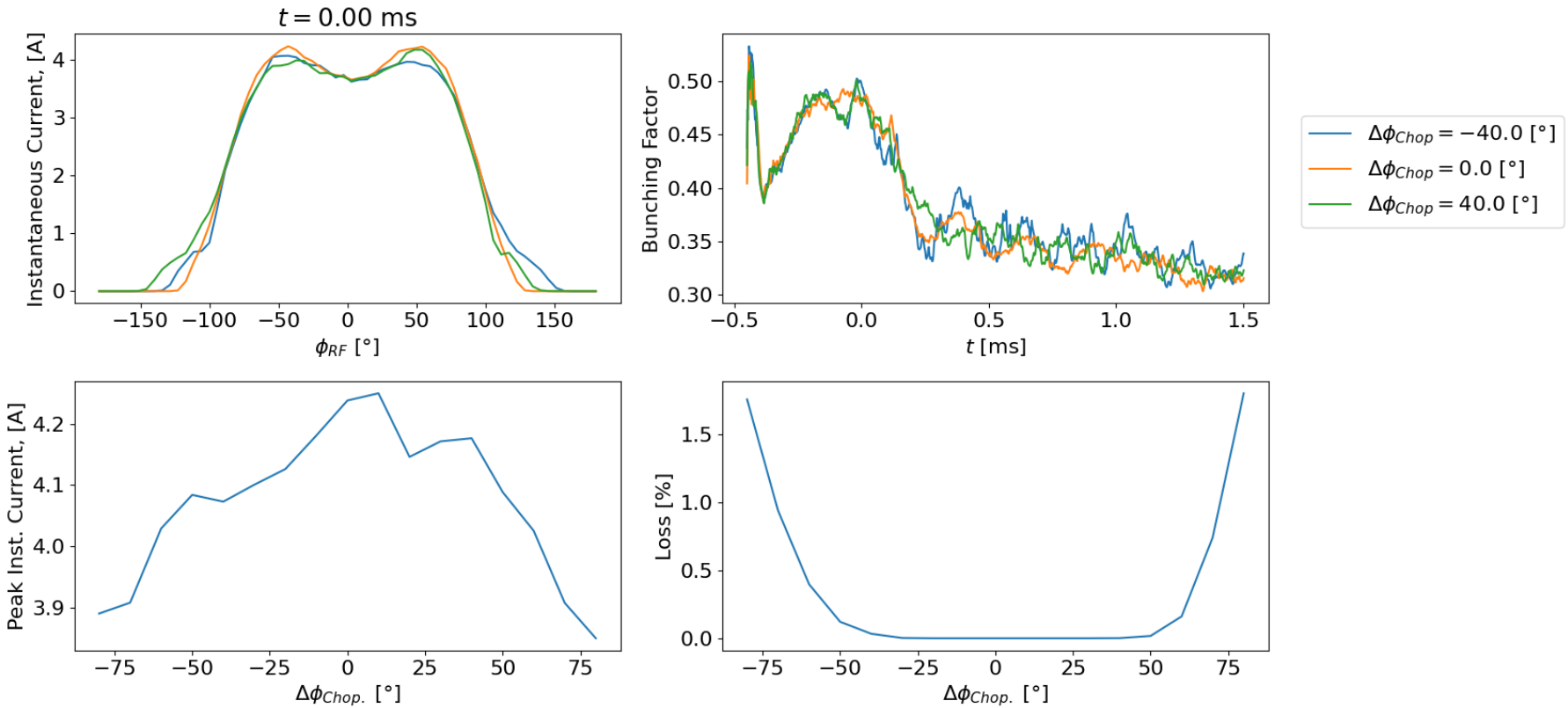


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Longitudinal Painting Study

- Chopper phase control enables painting
- Limited by
  - Relatively quick longitudinal motion ($Q_s \approx 0.005,\ N_{turns} \approx 190$)
  - Large phase extent of injector beam (1.2π rad)
- Linear painting in phase
  - Symmetric, outward, inward
- Outward may be beneficial
  - Small reduction in peak line density
  - Bunching factor marginally affected
- Scan ring RF frequency
  - Deforms bucket
  - Filamentation and trapping losses increase



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Summary

- MEBT chopper will enable zero-loss injection into ISIS RCS
- Voltage program developed for chopped injection mode
- Working point determined
- Operational stability analysis performed
- Chopped injection results in smoother LPS distributions, with reduced longitudinal emittance
- Small reduction in bunching factor expected, which may impact transverse space charge

Next Steps:

- Investigate 2nd-harmonic phase sweeps (à la J-PARC RCS [6])
- Non-linear chopper phase sweeps

Questions:

- Any experience of bunch shaping using ring RF frequency rather than e.g. PIMS?
- Successes with painting hollow beams and preserving them[7, 8]?

Thank you for your attention!
Any questions?

References

[1] ISIS Neutron and Muon Source, *"First Beam through Pre-Injector Test Stand"*, 2026

[2] S. R. Lawrie, *"External RF-Coil H^- Ion Source Commissioning"*, *presented at ICIS2021*, Canada (2021)

[3] J. Speed, A. Avaroglu and I. Rodriguez, *"Practical Design and Manufacturing of the New ISIS MEBT Chopper", in proc. of IPAC24,* USA (2024), doi: 10.18429/JACoW-IPAC2024-THPR19

[4] I. Rodriguez, S. Lawrie, and J. Speed, "*DESIGN OF AN ELECTROSTATIC CHOPPER FOR THE NEW ISIS MEBT", in proc. of IPAC23,* Italy (2023), doi: 10.18429/JACoW-IPAC2023-TUPM016

[5] S. Y. Lee , *"Accelerator Physics"*, Singapore (1999), World Scientific, ISBN: 981-02-3709-X

[6] F. Tamura *et al., "Longitudinal painting with large amplitude second harmonic rf voltages in the rapid cycling synchrotron of the Japan Proton Accelerator Research Complex", in Phys. Rev. STAB, 12*, 041001 (2009), doi: 10.1103/PhysRevSTAB.12.041001

[7] A. Oeftiger, S. Hancock and G. Rumolo, "*Space Charge Mitigation with Longitudinally Hollow Bunches", in proc. of HB2016,* Sweden (2016), doi:10.18429/JACoW-HB2016-MOPR026

[8] V. Forte *et al. "THE PSB OPERATIONAL SCENARIO WITH LONGITUDINAL PAINTING INJECTION IN THE POST-LIU ERA", in proc. of IPAC17,* WEPVA035, Denmark (2017), doi: 10.18429/JACoW-IPAC2017-WEPVA035