Bunching factor estimation for macroparticle beams

Practical study and results with ASTRA electron beams

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Introduction

Subheading, optional

01 First observations

- Past result
- Problem showcase
-

02 High number of macroparticles

- Challenges
- Improvements and results

03 Smoothing spline

- Introduction
- Improvements
- Results
- Limitations

General notes

- Simulations with ASTRA of smooth and modulated photocathode laser
- Gun at MMMG → 6.35 MeV/c
- Booster at MMMG-20deg → 17.0 MeV/c
- Most results at booster exit (4.51 m)
- Few examples with quadrupole transport
- Fourier analysis of ASTRA beams
- Bunching factor → relative amplitude of density modulation at given frequency

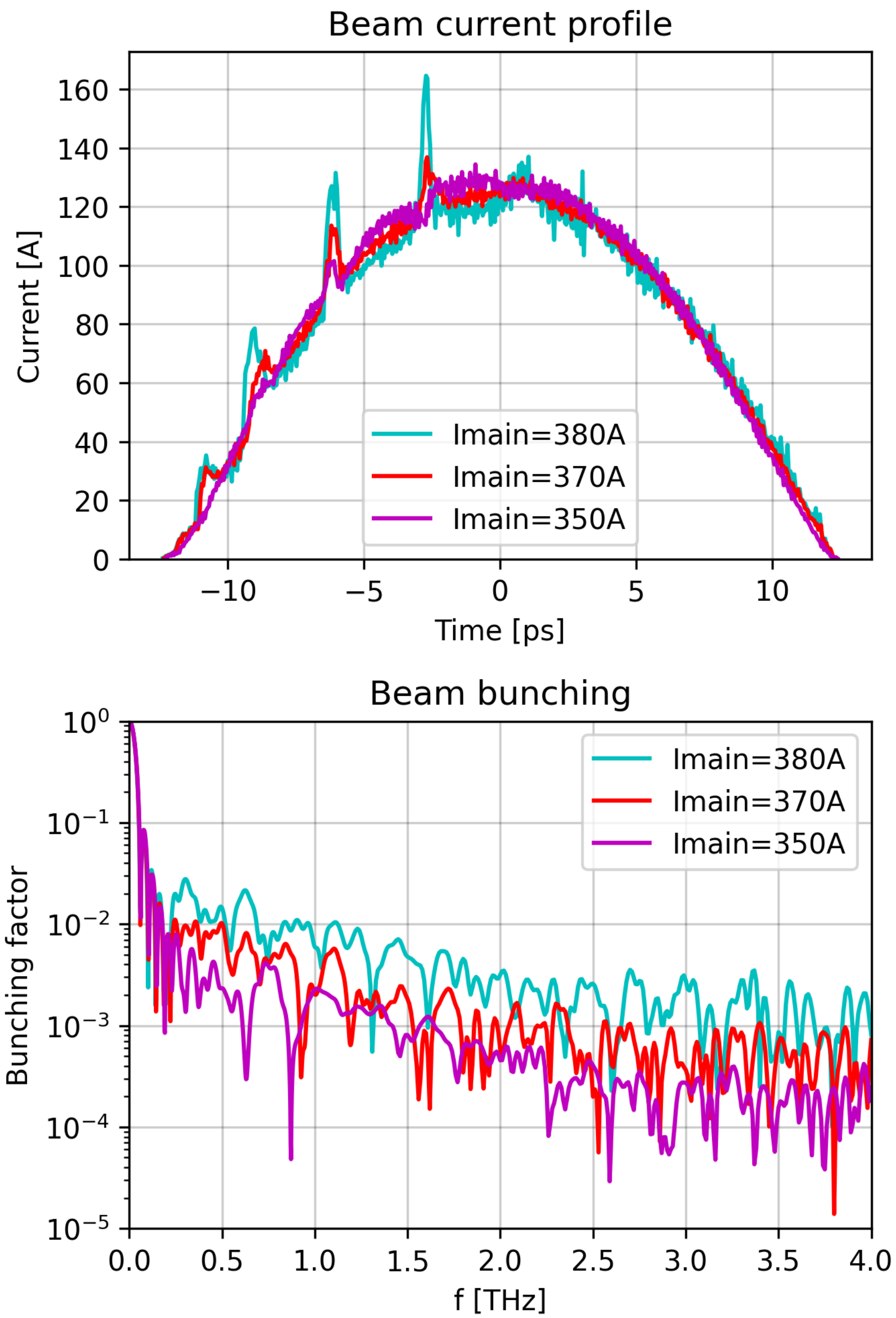
First observations

Simulation for sharp current spikes

- Modulated beam evolution with space-charge
  - Under right conditions → sharp spikes
- Main solenoid field
  - Focusing and density → space-charge
  - Non-linear SC with modulation → spikes
- Spikes development
- Bunching increase
  - Stronger solenoid → high frequency bunching

Incorrect conclusion!

Beam with 80% modulation at 4.51m, 2nC with 500k macroparticles



Simulation with smooth beams

- Long Gaussian photocathode laser profile
  - No modulations → no high freq. signal
- **Expected**: insignificant change by solenoid strength

Simulation with smooth beams

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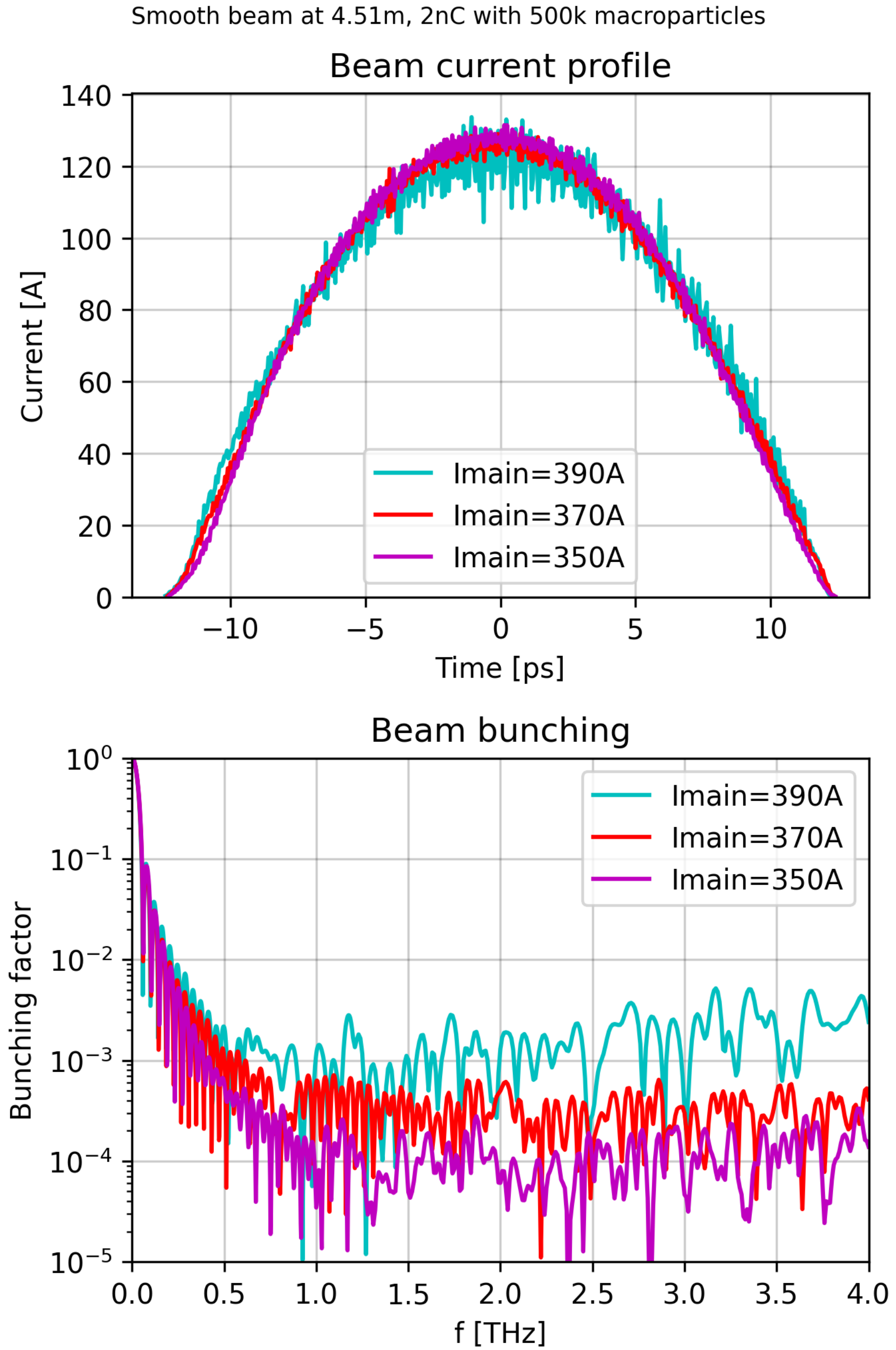
- **Expected**: insignificant change by solenoid strength
- **Observed**: increase at very high frequencies
  - Visible noise in beam current

Unphysical result!

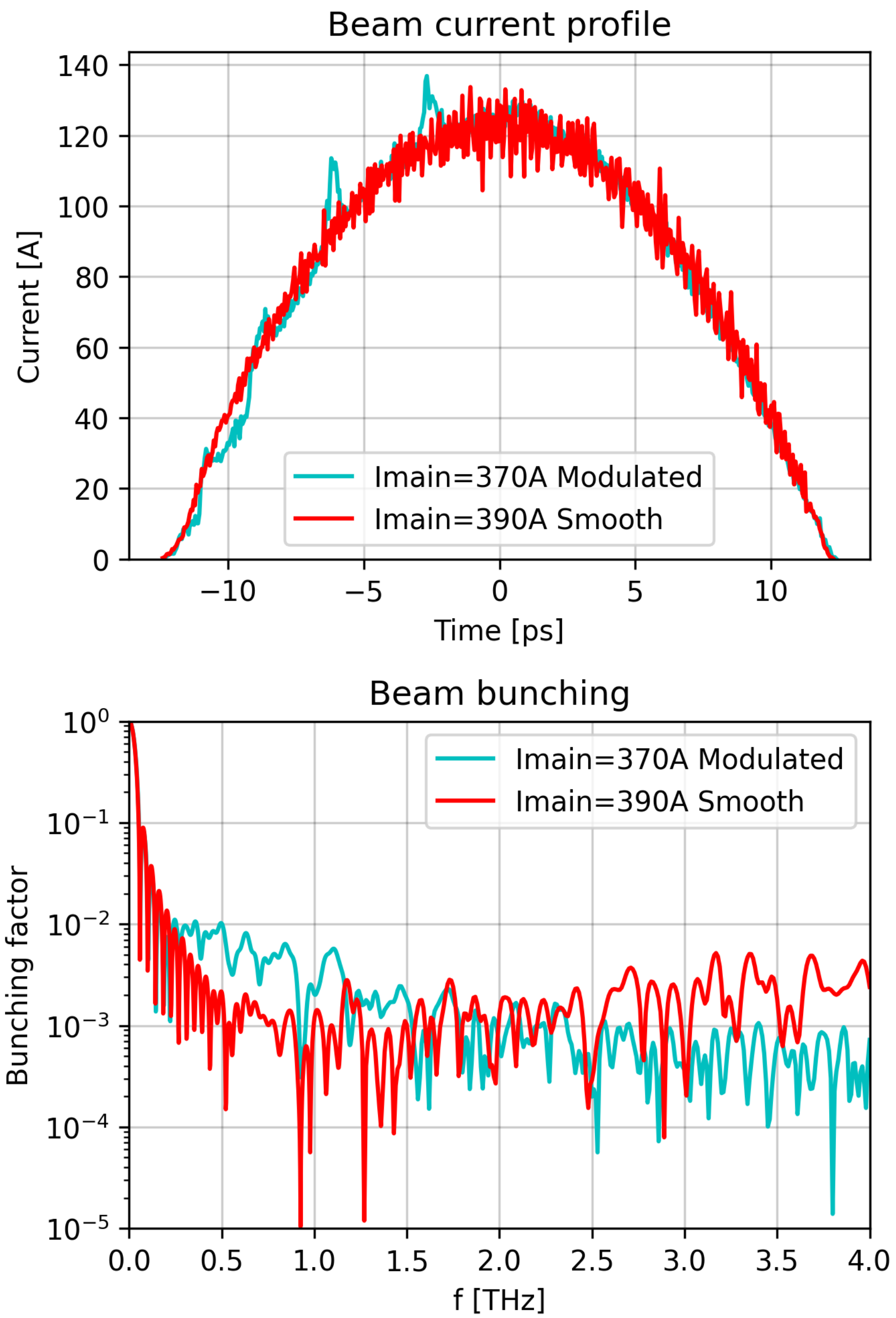
- Low number of macroparticles
  - Numerical noise (higher at high frequencies)
  - Enhanced by solenoid
  - ASTRA built-in noise reduction not sufficient



Severity of the problem

- Expected: modulations dominate high frequencies
- Numerical noise increase by solenoid
  - May overtake modulated beam
- Bunching factor analysis
  - Wrong results at higher frequencies
  - Noise baseline around 10^{-3}
  - Inadequate for FEL simulation setup

Beam at 4.51m, 2 nC with 500k macroparticles



Checkpoint

Subheading, optional

- Confirmed short spikes in beam current
- Difficult to analyze effect on bunching
  - Seeded FEL with short spikes – unclear
- Macroparticle numerical noise is high
  - Depends on main solenoid
- **Solution**: more macroparticles
  - Lower numerical noise
  - Increased simulation time
  - Increasing analysis time

Simulations with high number of macroparticles

Increased number of macroparticles

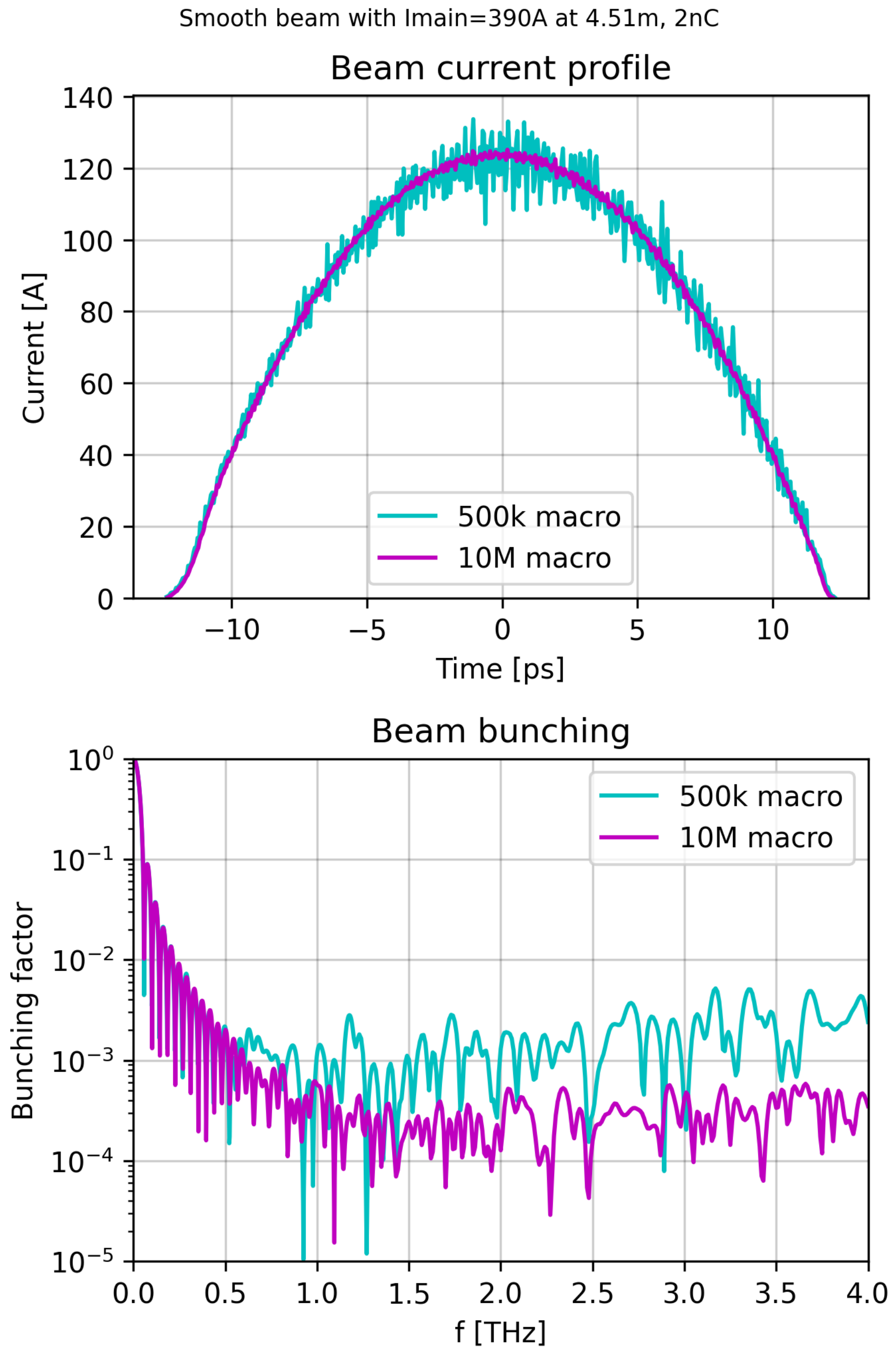
- Increase from 500k to 10M macroparticles
  - Double longitudinal space-charge binning
- Simulation execution
  - Over 30 h to get after solenoid
  - Over 33 h to booster exit
  - Over week? past undulator (still running...)
  - Requires ~4 GB RAM
  - Over 1 GB single beam file
- Very computationally intensive Fourier transform
  - Ideal method: particle by particle

Notes

- Cluster time limited to 48h per job
- Waiting time in queue for long jobs up to week
- AFS volumes can fill quickly

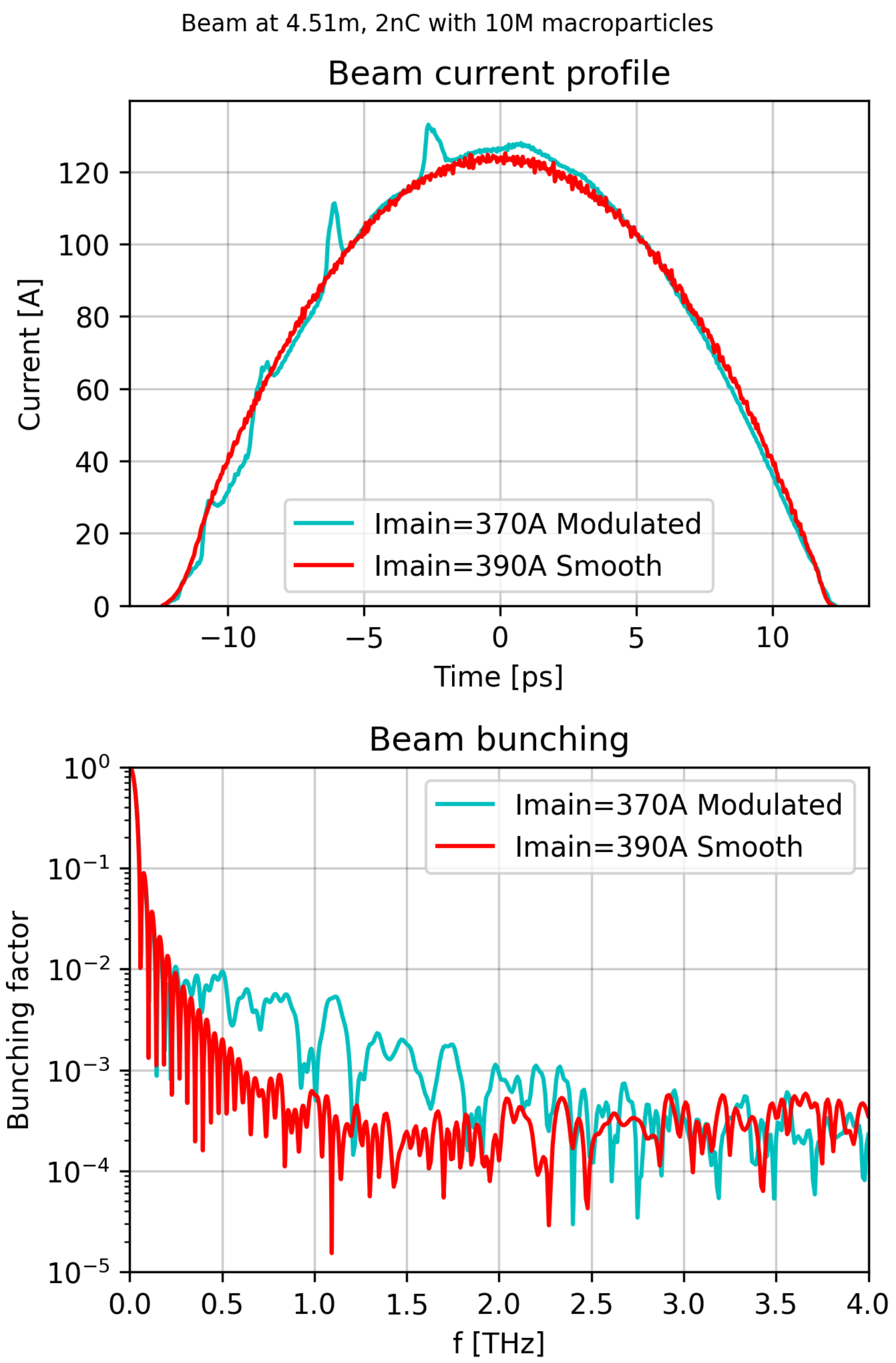
Comparison of 500k and 10M

- First demonstration of improvement
  - Noticeably lower noise in beam current
  - Order of magnitude lower bunching at 3 THz



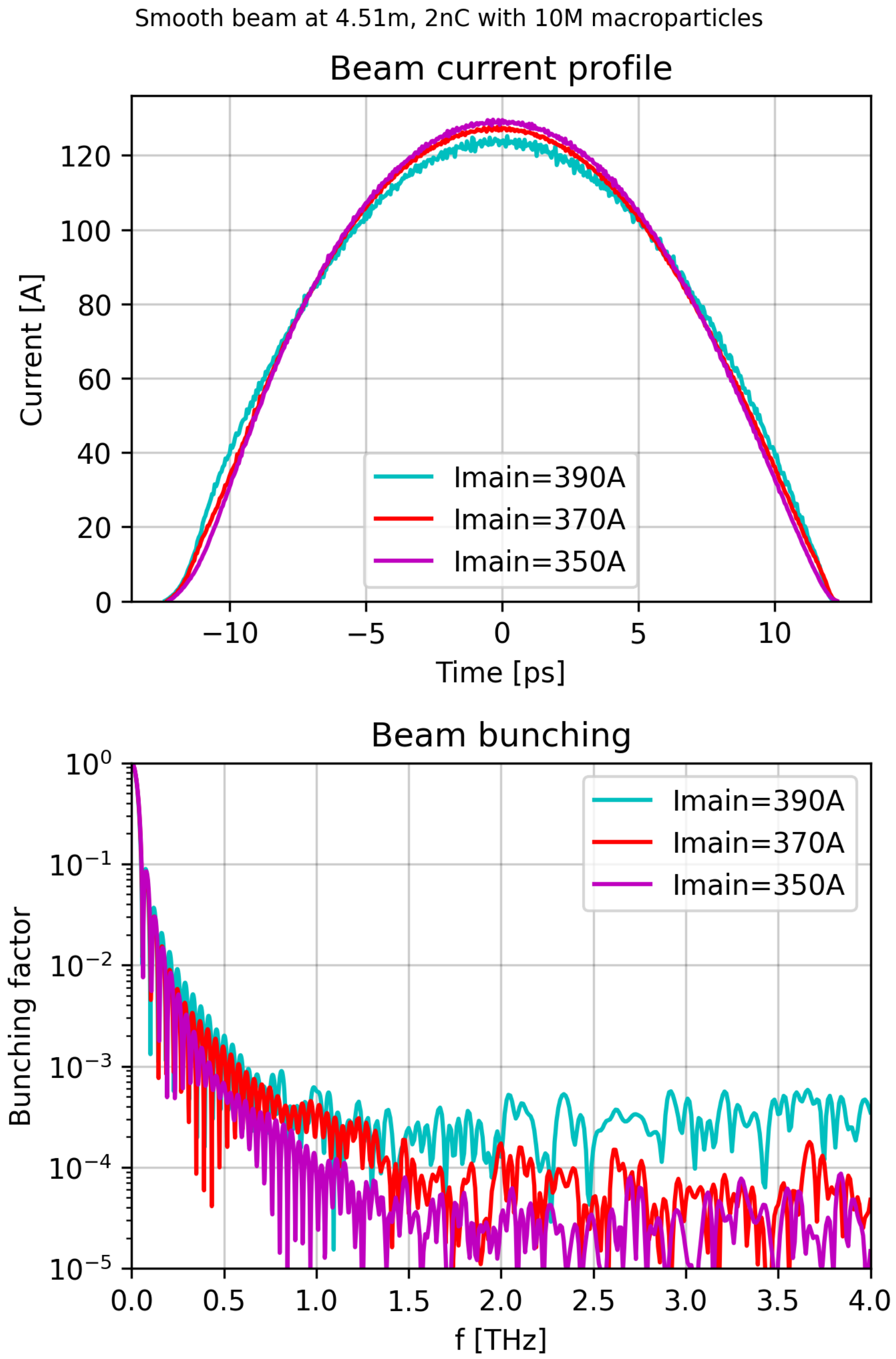
Severity of the problem II

- Expected: modulations dominate high frequencies
- Observed: up to ~2.5 THz only
- Better indication for seeding?
  - Still misleading
  - Noise baseline between 10^{-4} to 10^{-3}



Simulation with smooth beams

- Reference smooth beam comparison
  - No modulations → no high freq. signal
- **Expected**: insignificant change by solenoid strength
- **Observed**: increase at very high frequencies
- Main problem remains
  - Macroparticle numerical noise is high
  - Depends on main solenoid
- Unclear effect of seeding at 3 THz
  - Hidden in noise? Actual level?



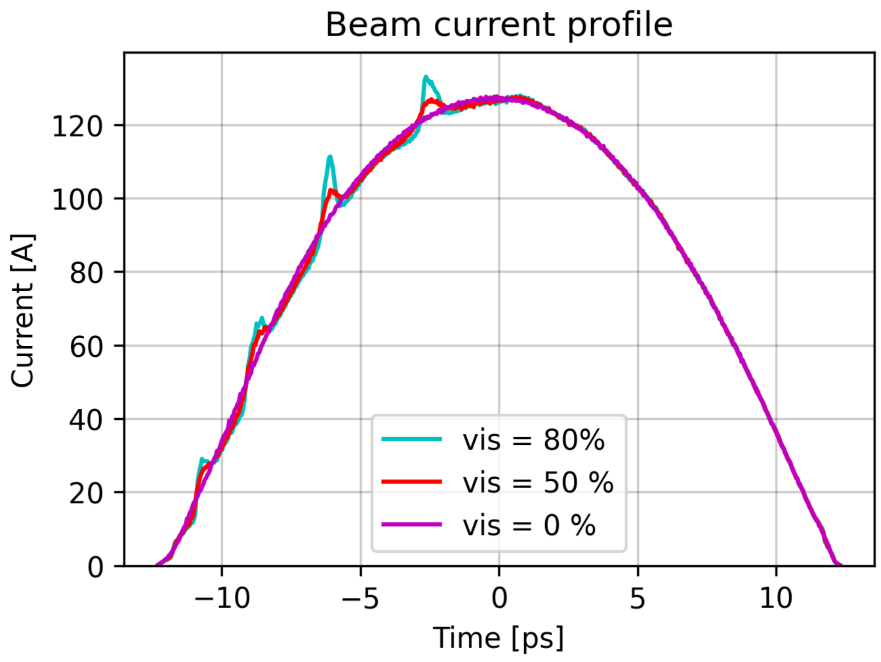
Result: laser modulation visibility

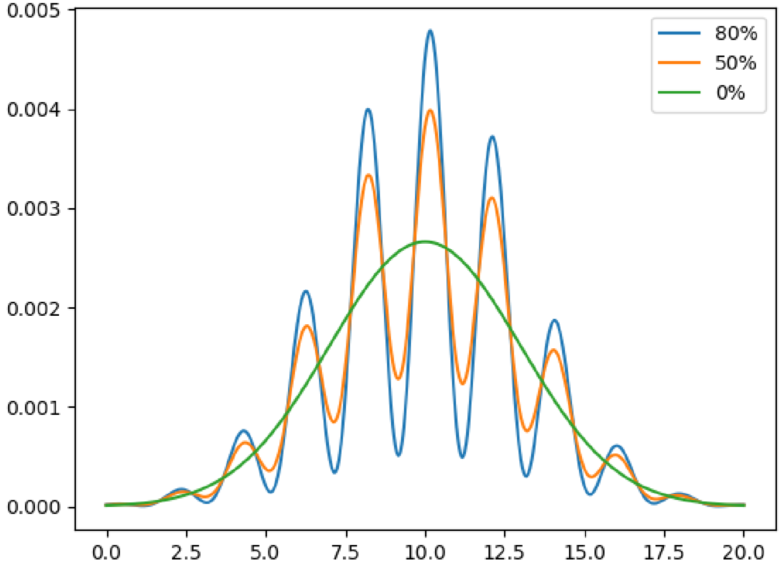
- Defined by interferometric visibility

$$V = \frac{MAX - MIN}{MAX + MIN}$$

- Sharp spikes development
  - Sensitive to initial modulation visibility
- Crucial for experiment

Modulated beam at 4.51m, 2nC with 10M macroparticles

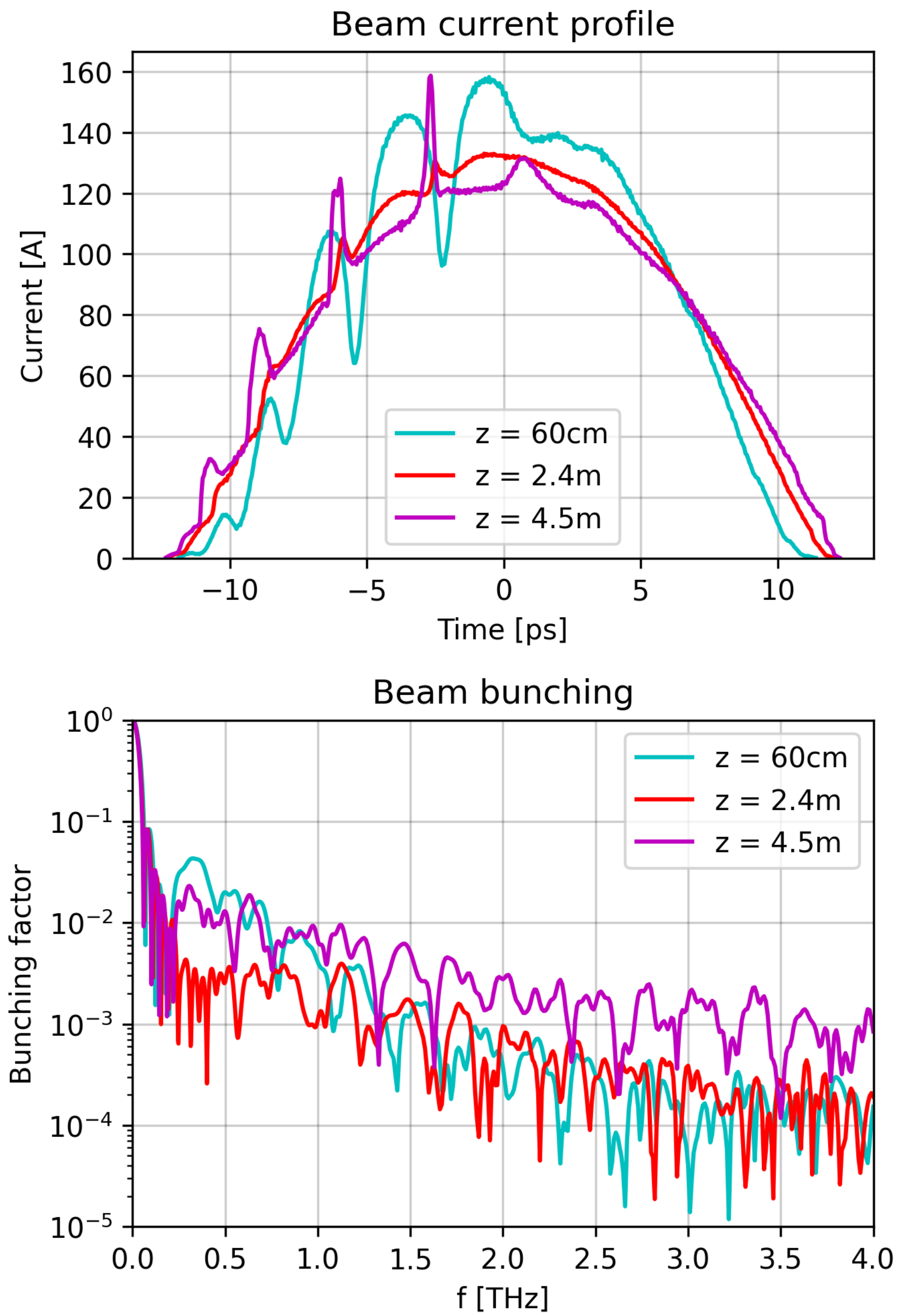




Result: sharp spikes development

- Non-linear SC + modulations → sharp spikes
- 0° phase – initial modulation
  - Blue line, SC smeared
- 90° phase – modulations vanish (red line)
- 180° phase – high harmonics of base modulation
  - Constructive interference
- Note: bunching analysis inconclusive

Beam with 80% modulation Imain=380A, 2nC with 10M macroparticles



Checkpoint

- Increased number of particles 20 times
- Challenging simulation and analysis
- Lower macroparticle noise
  - Depends on solenoid, unclear baseline
  - Around 10^{-4} bunching, too high for FEL
- Overall improvement, but insufficient
- Better analysis will give important benefits!

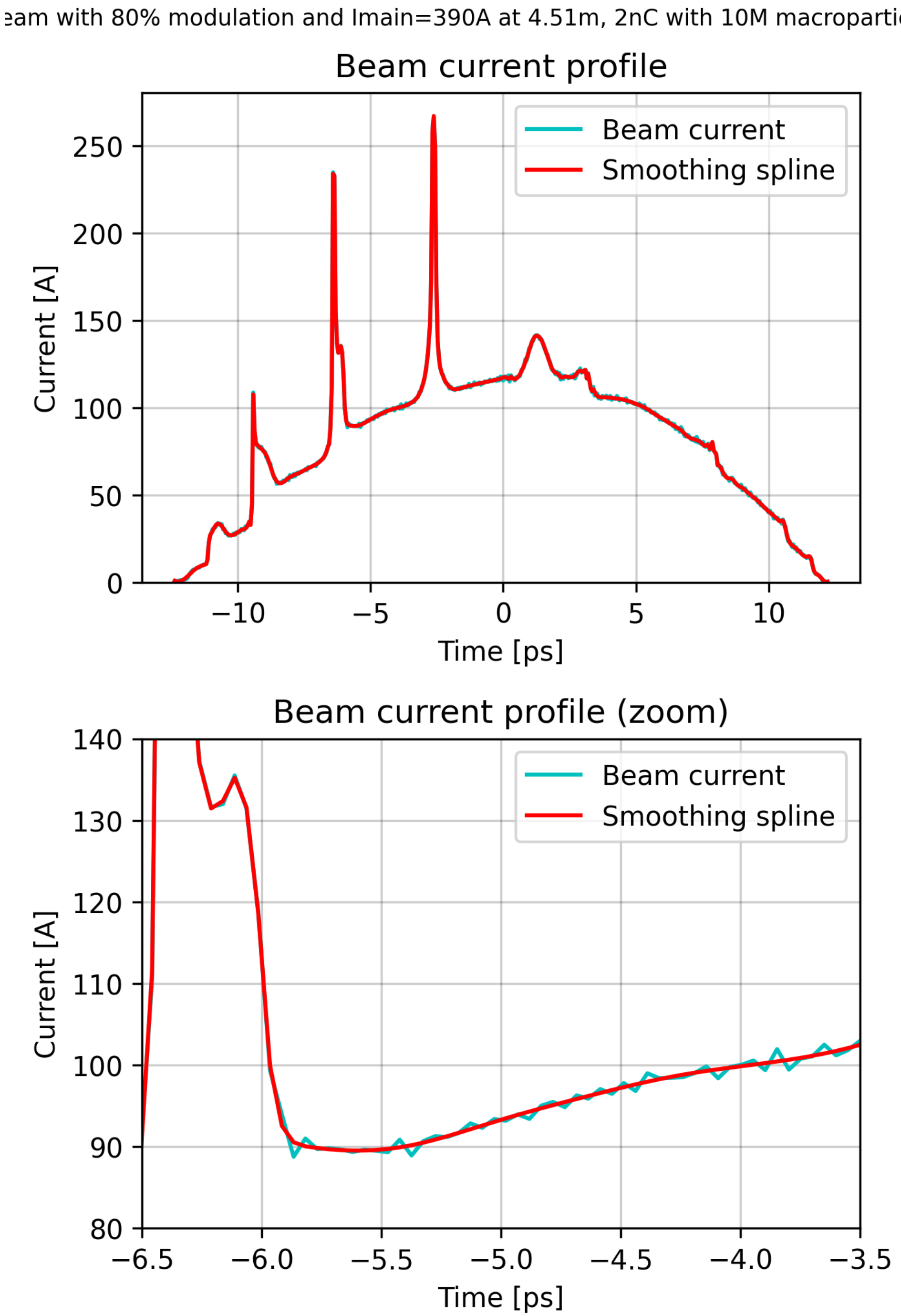
Analysis with smoothing spline

Introduction

- Spline curve – interpolation
  - Minimizes overall surface curvature
  - Second order continuity
  - Passes through input points
- Spline smoothing
  - Piecewise polynomials (not convolution)
  - May choose new anchors (not input points)
  - Beneficial behavior

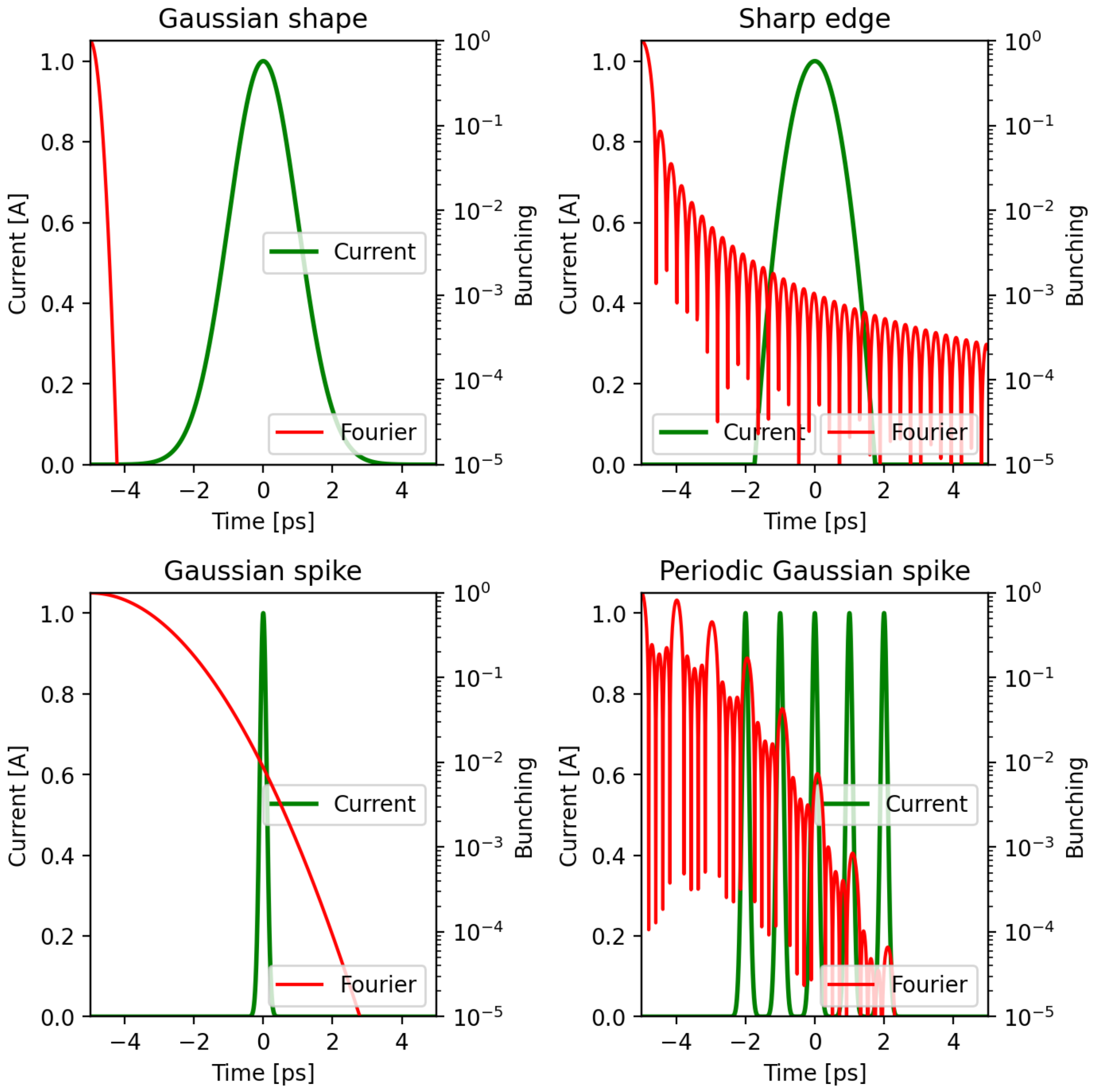
Introduction

- Spline curve – interpolation
  - Minimizes overall surface curvature
  - Second order continuity
  - Passes through input points
- Spline smoothing
  - Piecewise polynomials (not convolution)
  - May choose new anchors (not input points)
  - Beneficial behavior
- **Ignores small fluctuations**
- **Preserves prominent features**



Notes to Fourier analysis

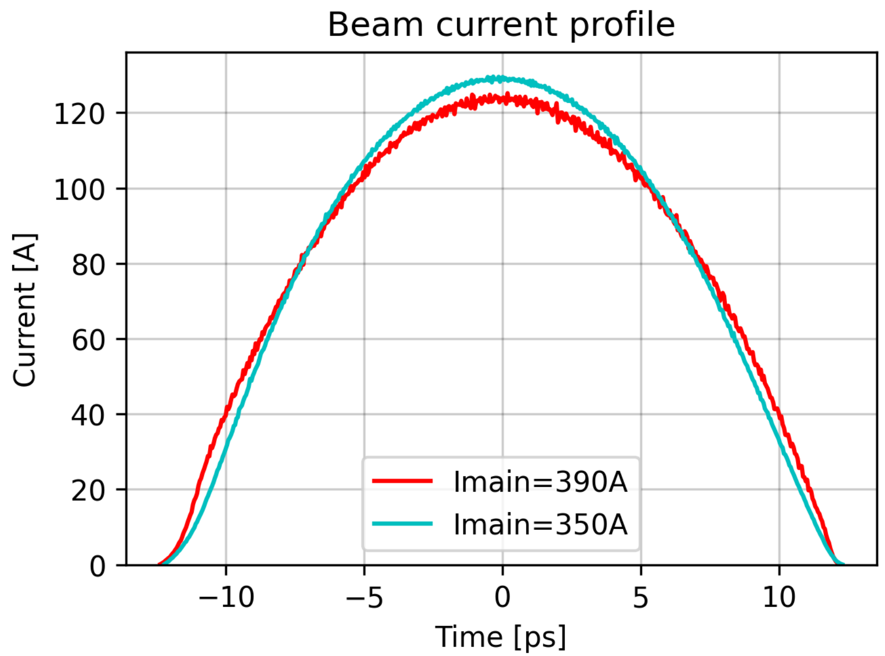
- Long Gaussian → narrow spectrum
- Short Gaussian → wide spectrum
- Repeated spikes → harmonics in envelope
- Sharp edge → long tail of repeated peaks

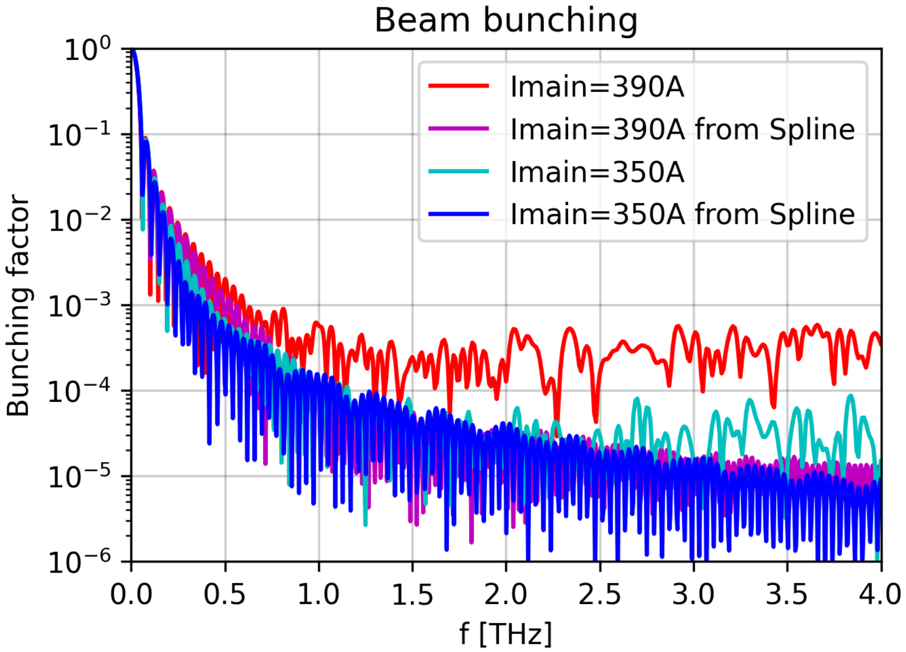


Analysis with smooth beams

- Reference smooth beam comparison
  - No modulations → no high freq. signal
- **Expected**: insignificant change by solenoid strength
- **Observed**: insignificant change!
- Provides consistent noise floor
- Noise levels ~10^{-5} bunching at 3 THz
  - From Genesis simulations: no seeding effect

Smooth beam at 4.51m, 2nC with 10M macroparticles

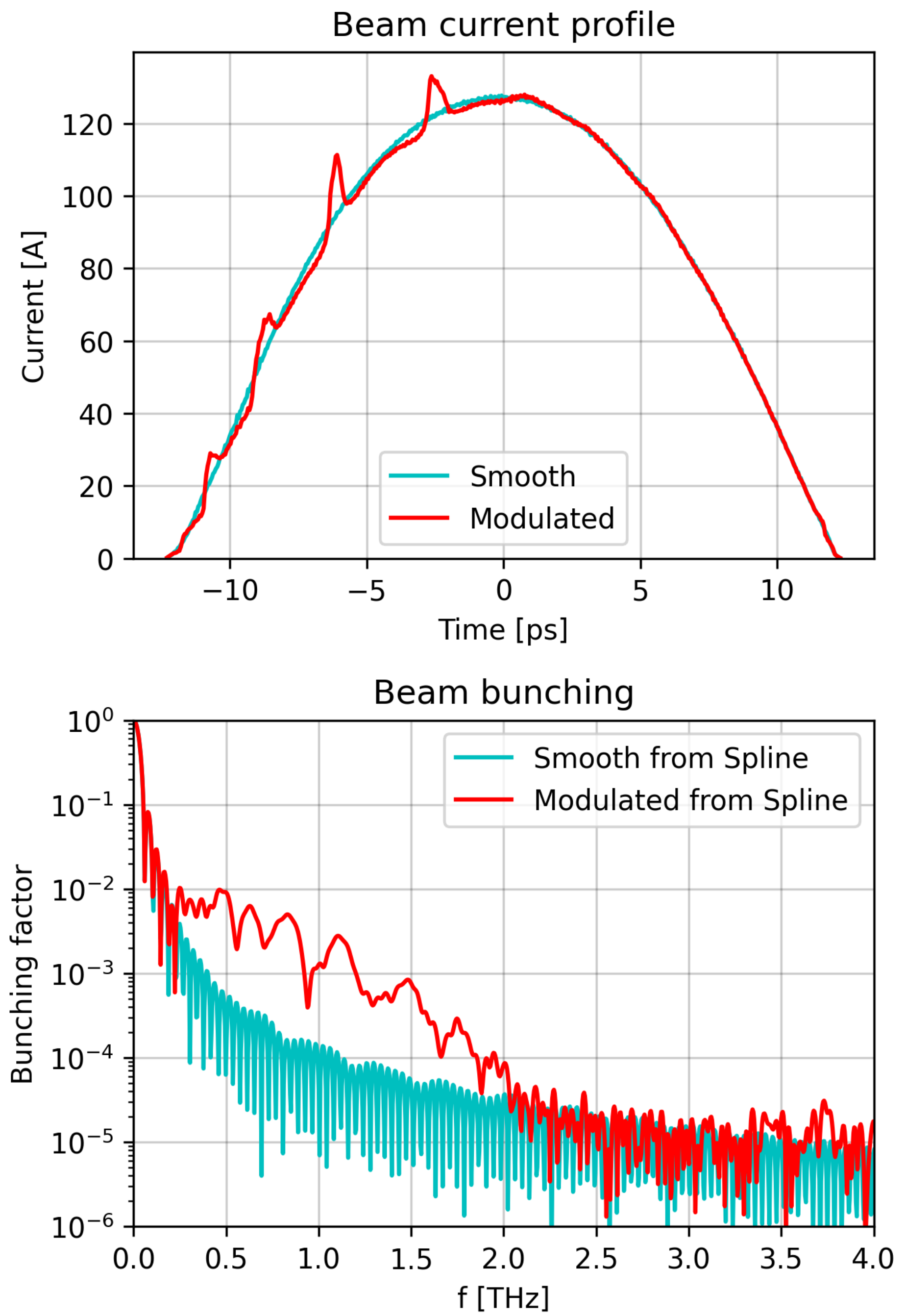




Bunching from modulated beam

- Slightly developed sharp spikes
- Clearly increased bunching factor
  - From base modulation up to ~2 THz
  - Nothing at 3 THz!

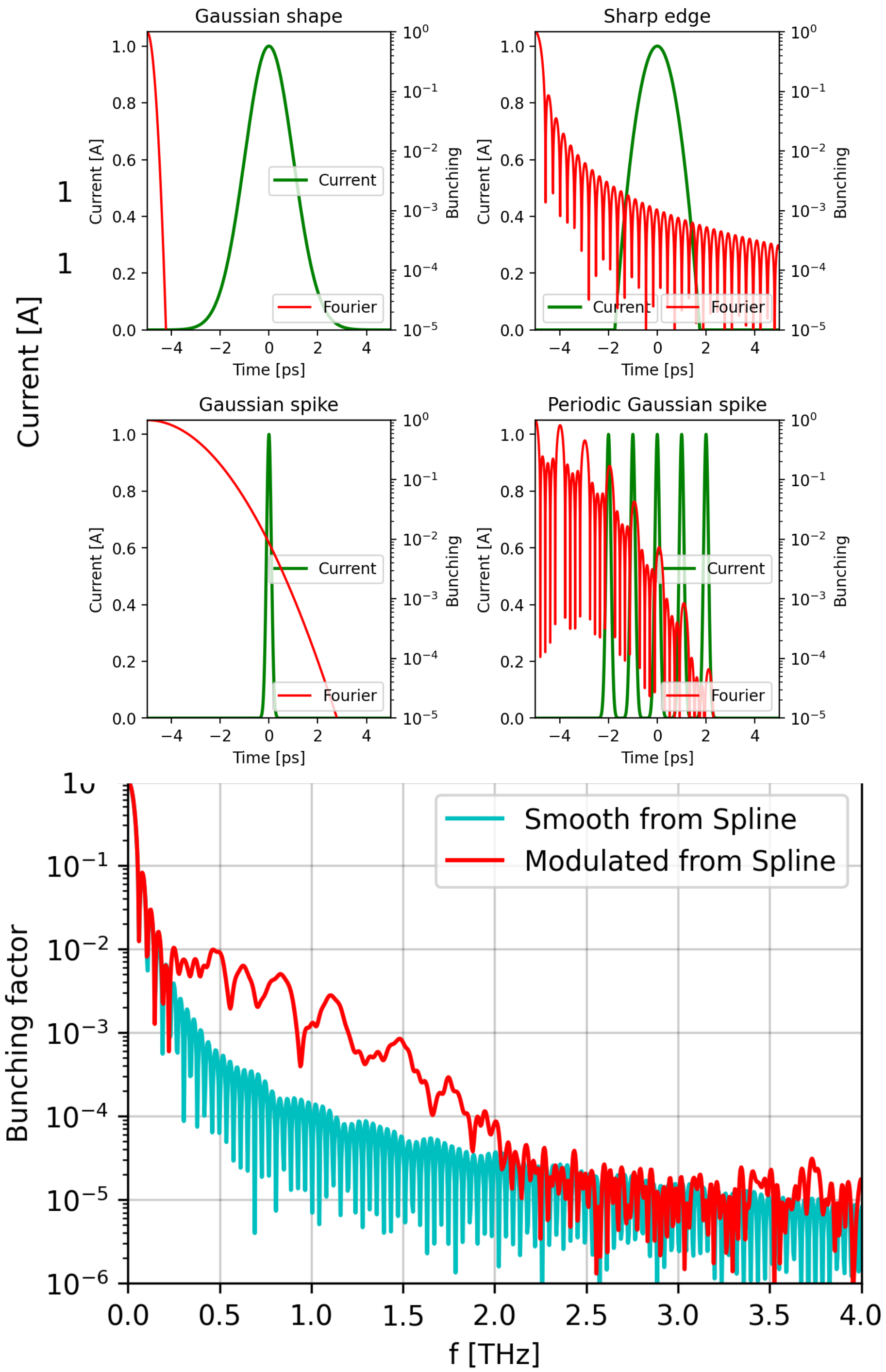
Beam with Imain=370A at 4.51m, 2nC with 10M macroparticles



Bunching from modulated beam

- Slightly developed sharp spikes
- Clearly increased bunching factor
  - From base modulation up to ~2 THz
  - Nothing at 3 THz!
- Regions in bunching over frequency
  - Narrow base peak
  - Harmonic peaks to wider frequency
  - Sharp edge baseline

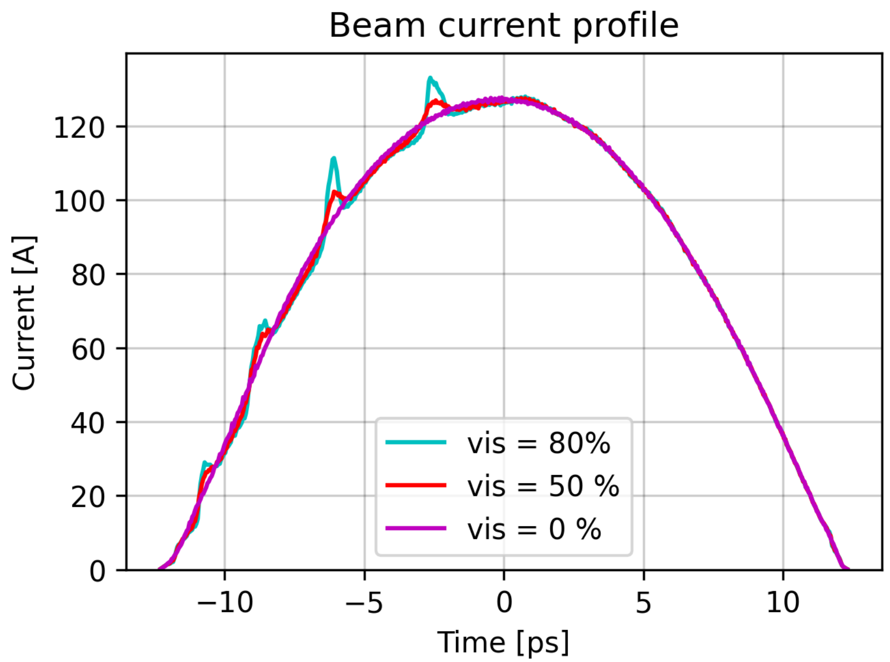
Analysis limited by tail edges in current profile!

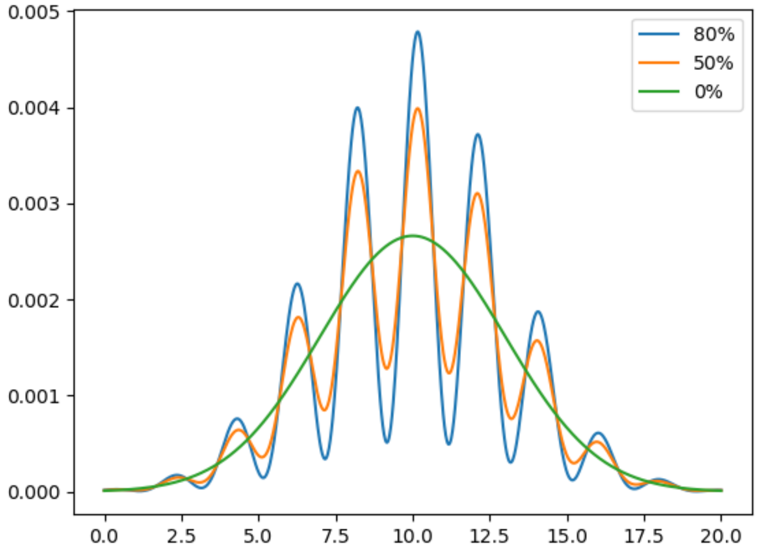


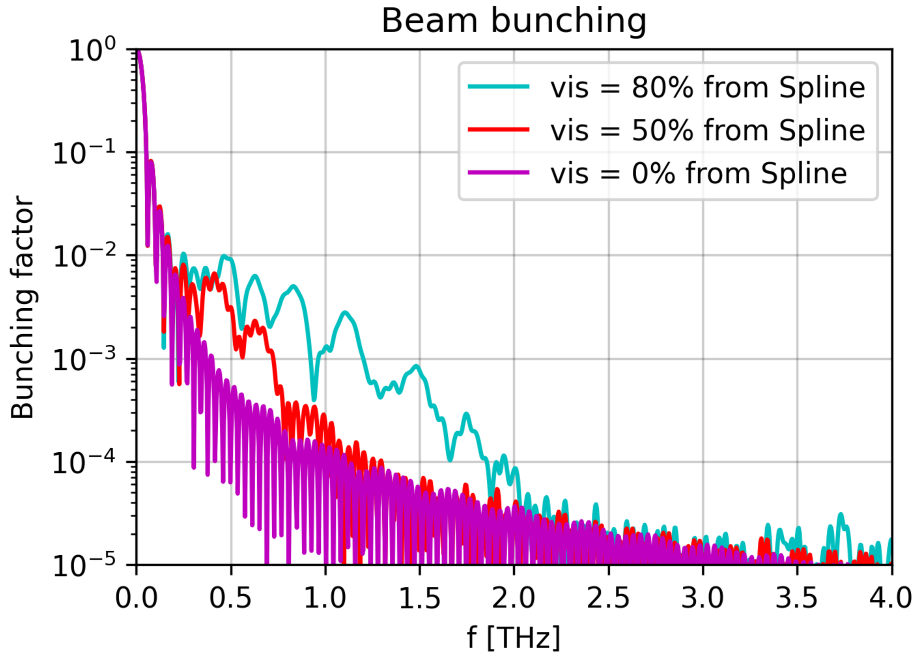
Result: laser modulation visibility

- Lower visibility → severely limited sharp spikes
- At 80% → up to 2 THz
- At 50% only up to 1 THz
- **Crucial for the experiment**

Beam with Imain=370A at 4.51m, 2nC with 10M macroparticles





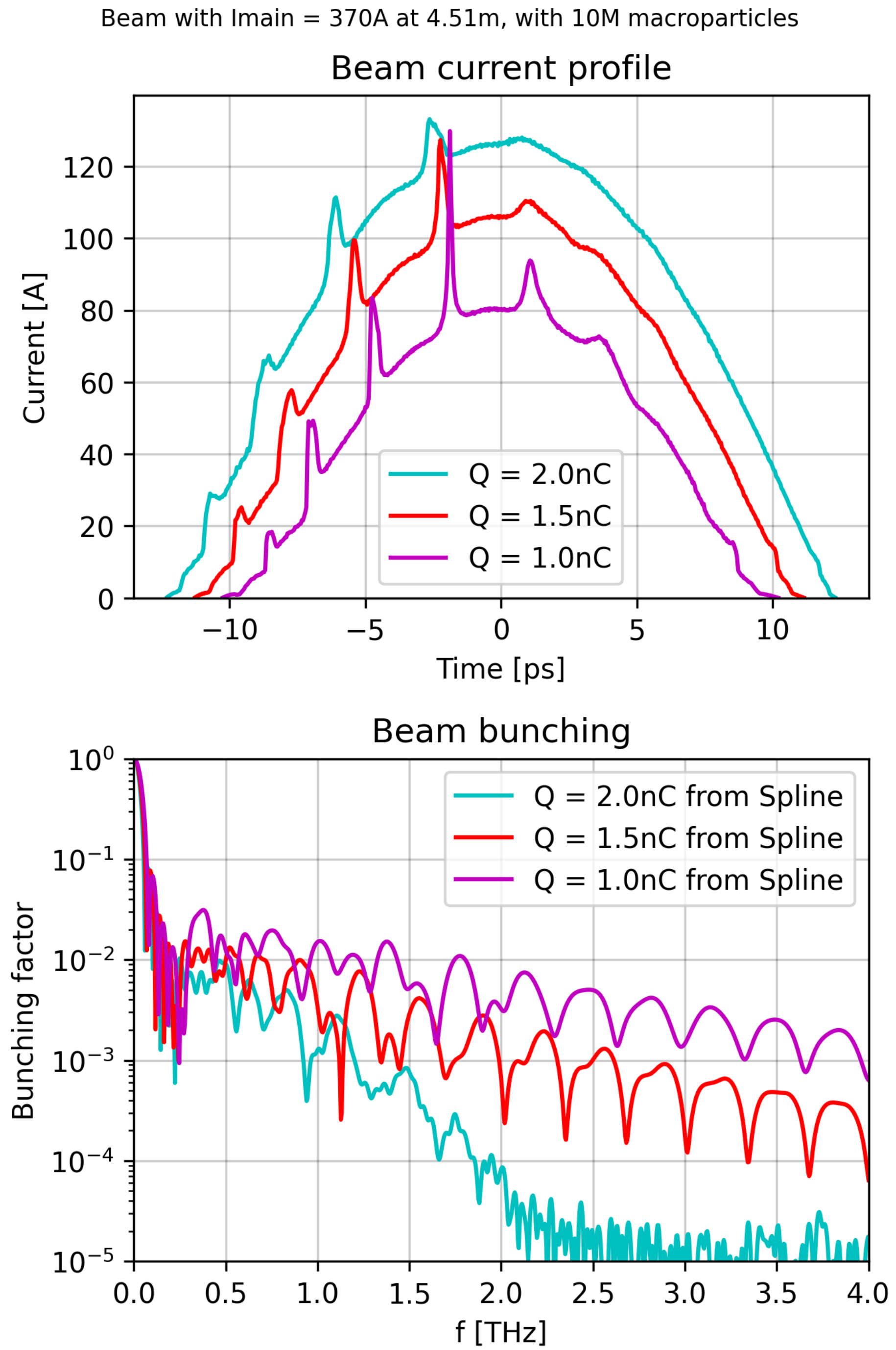


Result: bunch charge effects

- Non-linear effect from space charge forces
  - Strong dependence on charge
- Expected: higher charge → more non-linear SC

Result: bunch charge effects

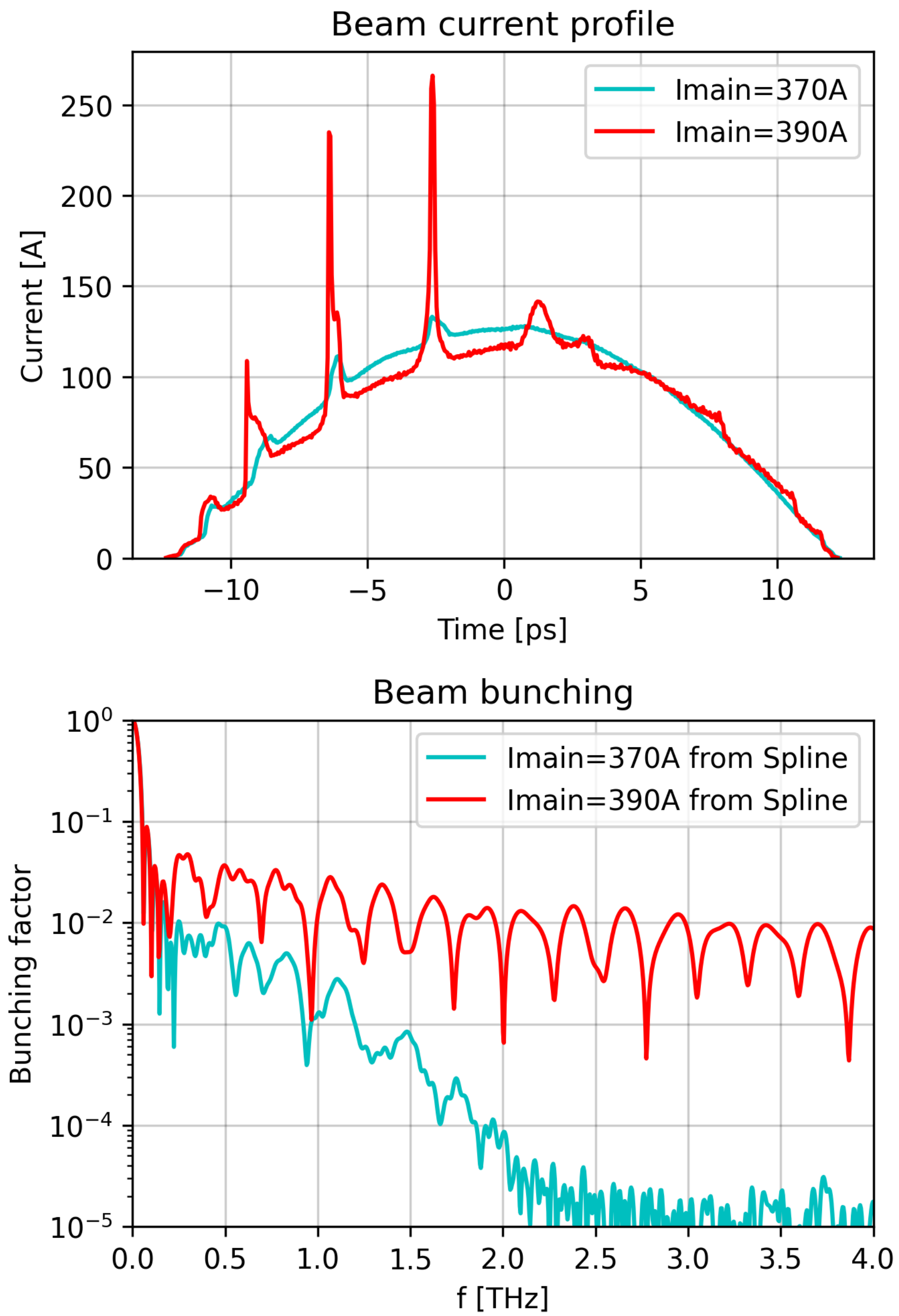
- Non-linear effect from space charge forces
  - Strong dependence on charge
- Expected: higher charge → more non-linear SC
- Observed: spikes develop faster at low charge
- Bad: FEL process benefits from charge
- Good: developed spikes → high bunching
  - Bunching factor 10^{-3} at 3 THz
  - Very efficient seeding



Result: solenoid focusing

- Better sharp spike development
  - Observed as expected
- **Very strong bunching at very high frequencies**
- Compromise with beam transport
  - Emittance control also by solenoid

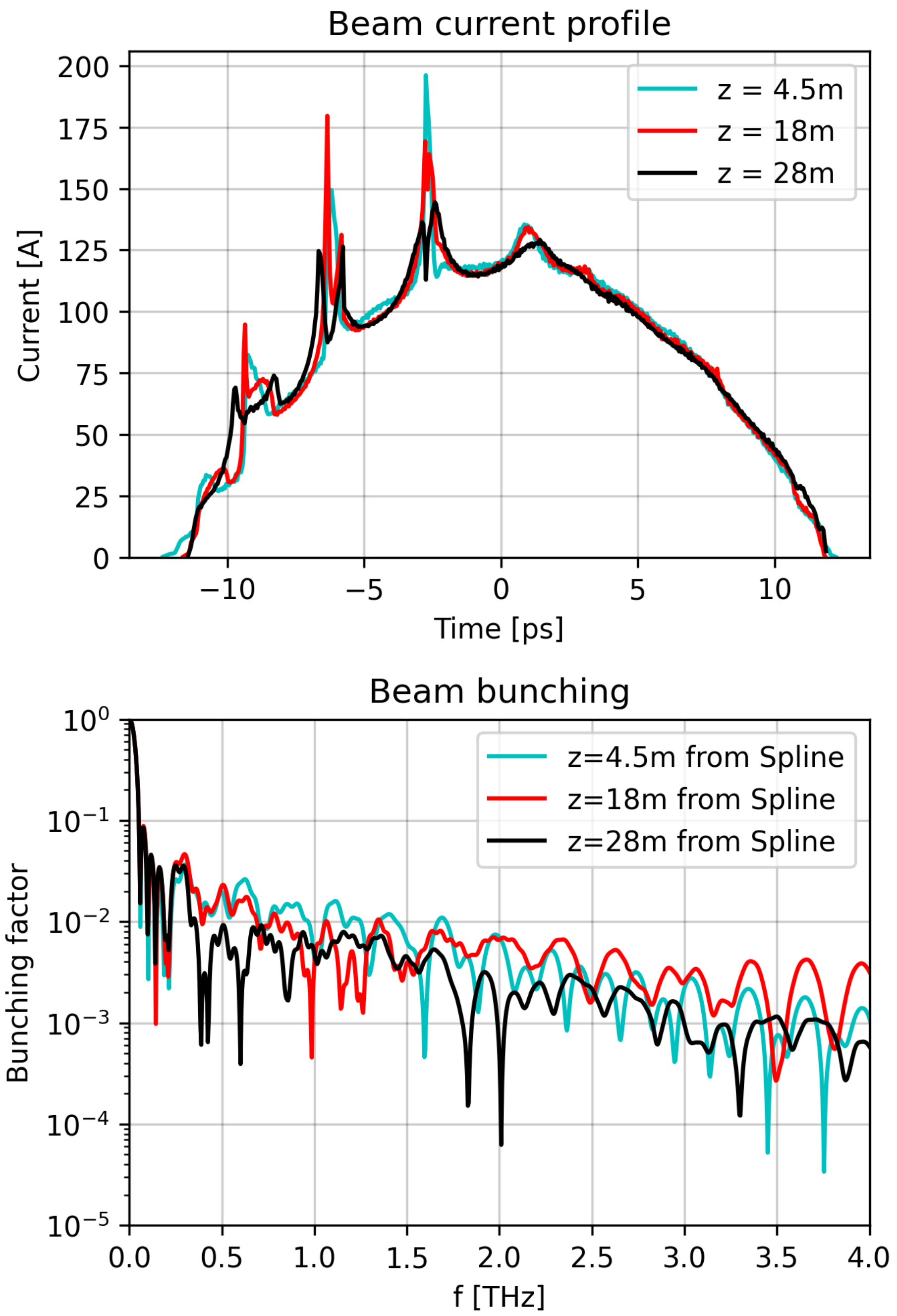
Beam with 80% modulation at 4.51m, 2nC with 10M macroparticles



Result: transport to undulator

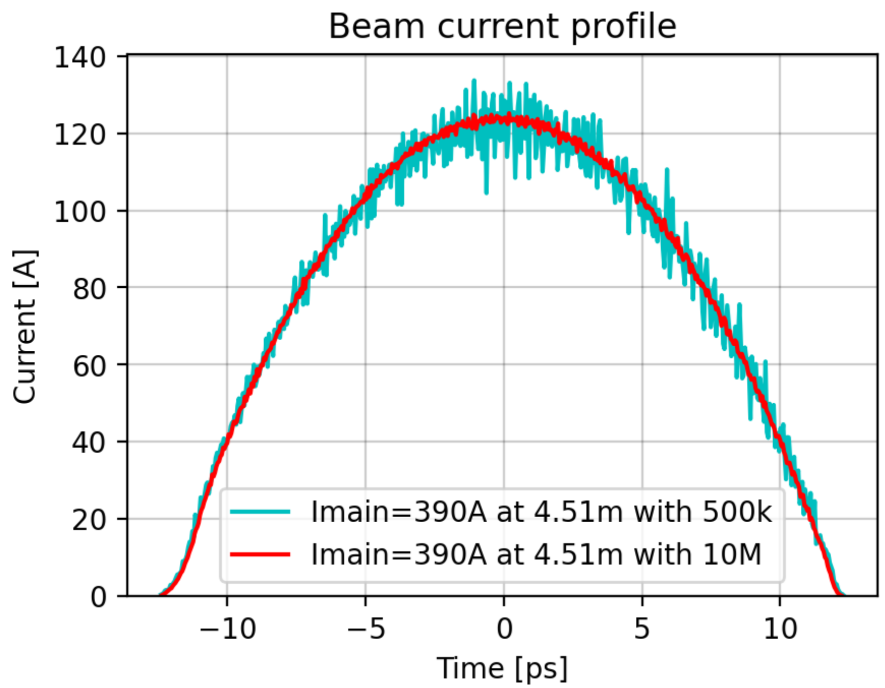
- Space charge forces frozen in high section
  - Some effect
  - Longitudinal phase-space modulation
- Spikes development continues slowly
- Start to degrade past some point
  - High bunching mostly preserved
  - Transport is not main challenge

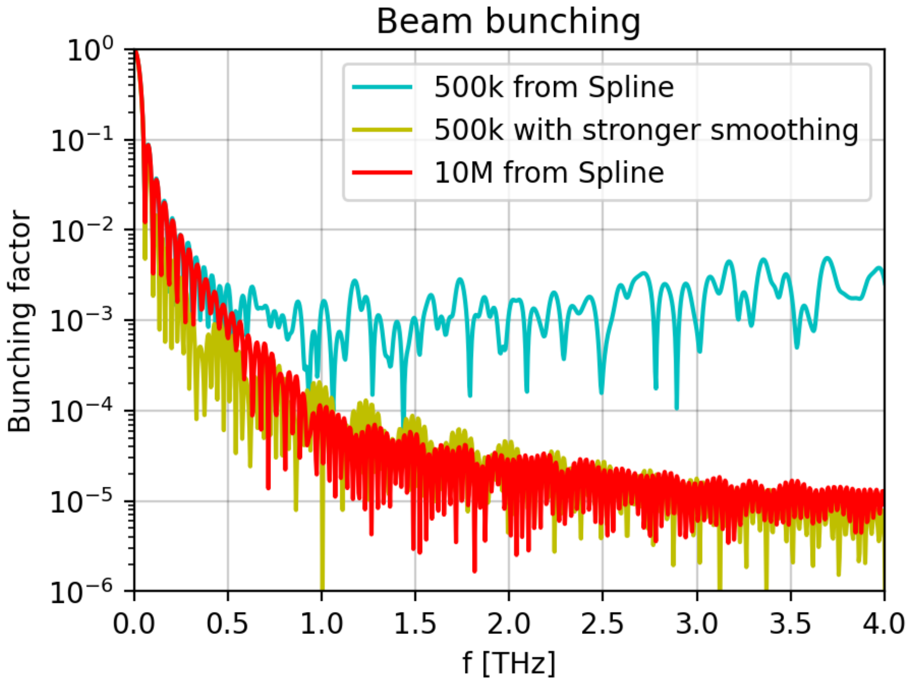
Beam with 80% modulation Imain=385A, 2nC with 10M macroparticles



Limitation of analysis

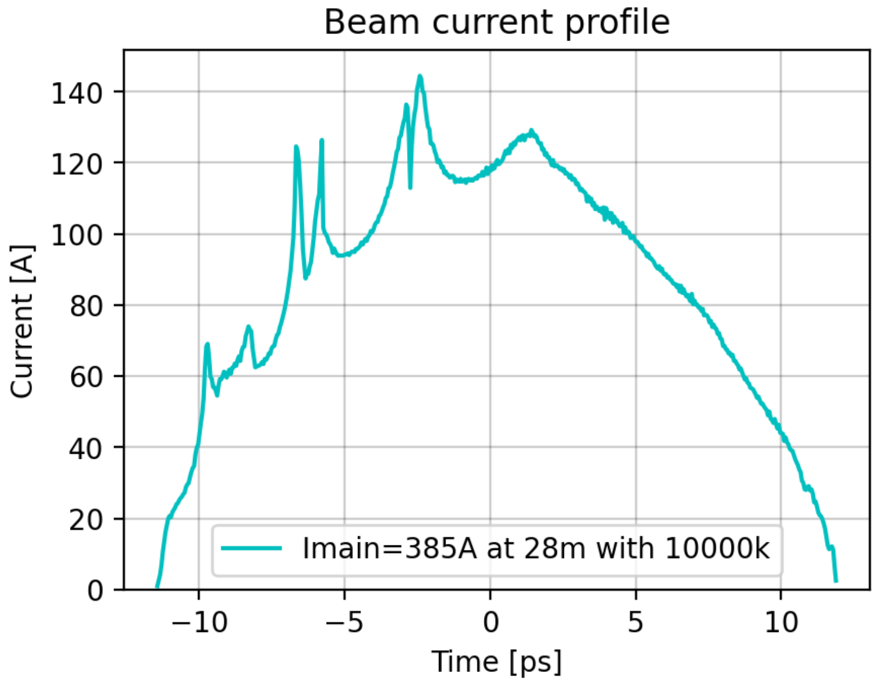
- Spline smoothing effective on small noise
- Strong prominent noise is not smoothed
- Less particles require **stronger smoothing** value

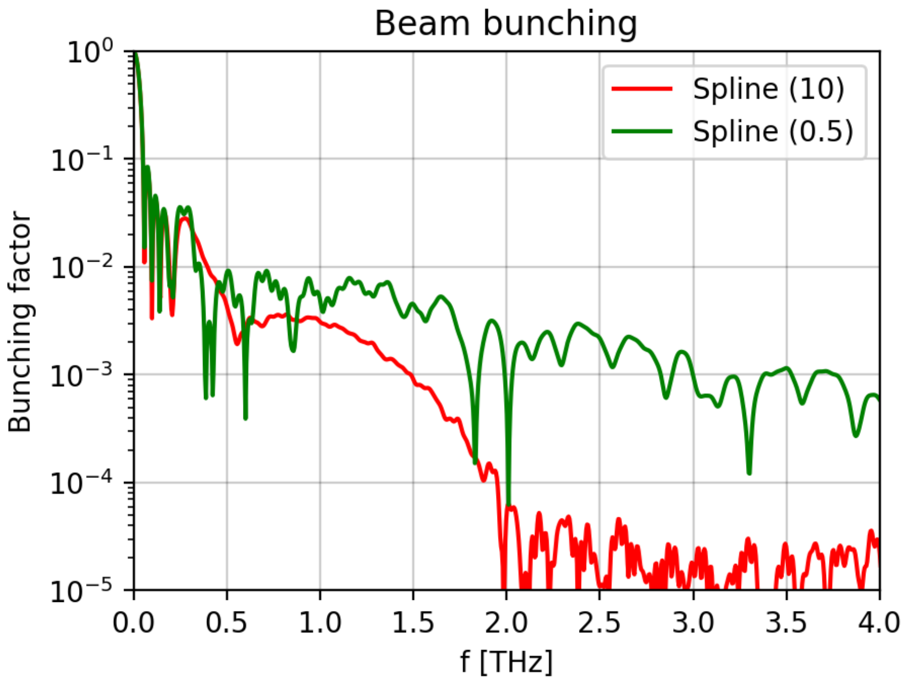




Limitation of analysis

- Spline smoothing effective on small noise
- Strong prominent noise is not smoothed
- Less particles require **stronger smoothing** value
- Stronger smoothing has effect on features
  - Can smooth sharp spikes
  - Puts back question on bunching factor





Conclusion

Bunching factor estimation

- Shot noise is a major challenge in simulated beams
- Special analysis with smoothing spline
  - Preserves features, clears noise
- Spline smoothing requires good start
  - Noise much lower than features
  - Increased smoothing changes behavior
- With 10M macroparticles → enough for 3 THz
- Simulation setup and analysis → few weeks work
  - Tricky: practical and artificial limits
  - Computationally heavy (high budget)
  - Compromise: 3M macroparticles?

Results

- Photocathode laser modulation → crucial
- Solenoid and beam charge → key
- Sharp spikes can provide bunching at 3 THz

Outlook

- Experimental confirmation

Thank you