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Coherent Synchrotron Radiation and Microbunching Instability at FERMI

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Contents

1) Coherent Synchrotron Radiation

2) Microbunching Instability

3) Conclusions & Future Work

Note: This talk is about CSR and MBI in **FELs**, not rings

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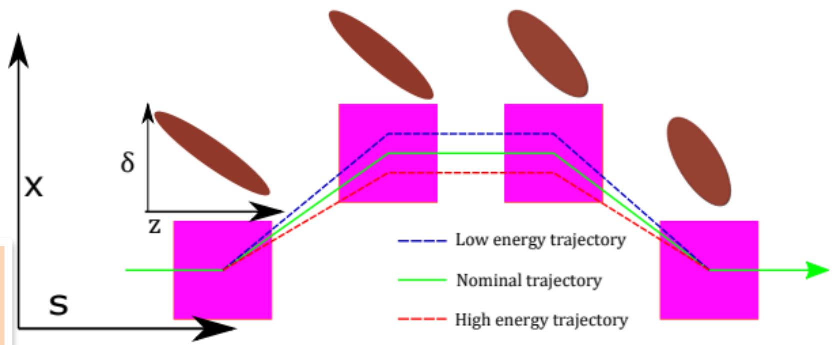
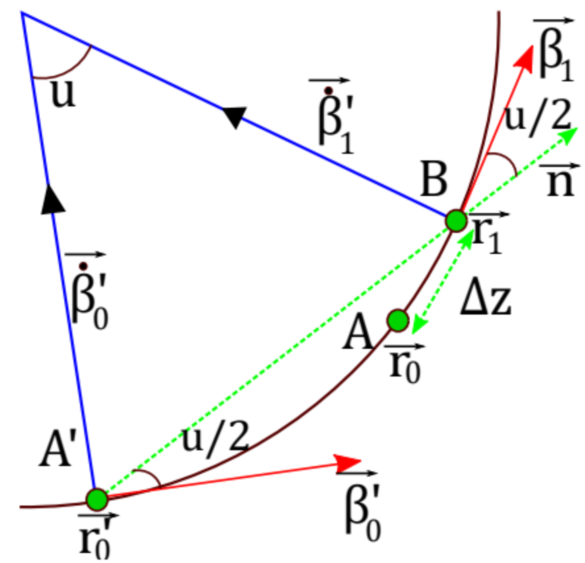
CSR - Theory



Bunch compressor chicane and beam evolution

Causes and Consequences

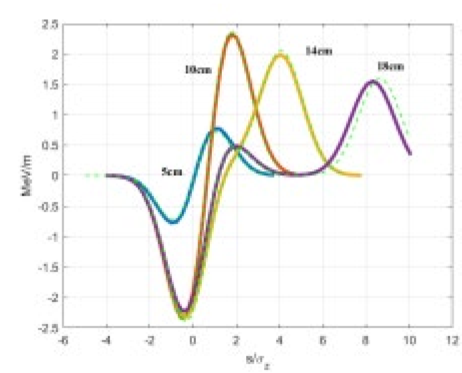
- Free-electron lasers (FELs) require **high-brightness electron bunches**.
- This requires longitudinal compression, most commonly achieved in a chicane-like **bunch compressor**.
- Due to the **curved trajectory** of the electrons, the **radiation** emitted by trailing particles can influence those in front of it, leading to **emittance growth** and **microbunching** [1,2].



Radiative interaction between trailing and leading particle in a dipole

Theoretical Approaches

- Solving for the full electric field radiated is difficult analytically, so some **assumptions** have to be made:
  - **1D projection** of the charge density [3]?
  - **Stochastic effects** due to the long-range interaction between radiation cones [4]?
  - **Rigid longitudinal movement** of the beam?



CSR wake potential through a bending magnet

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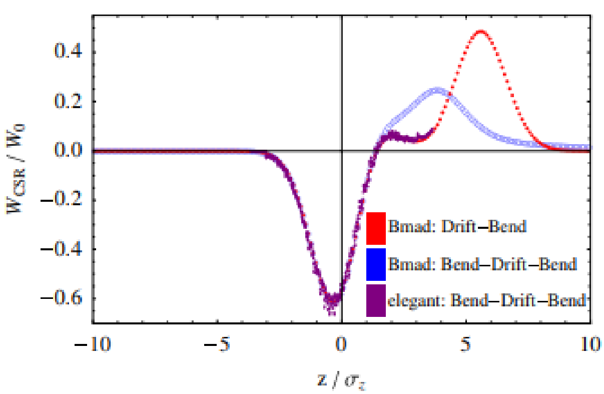
CSR - Simulations

COMPUTATIONAL EFFORT

1D Approach

- Projects the bunch density onto the longitudinal axis to compute the fields.
- Simplest to implement.
- Can sacrifice accuracy.

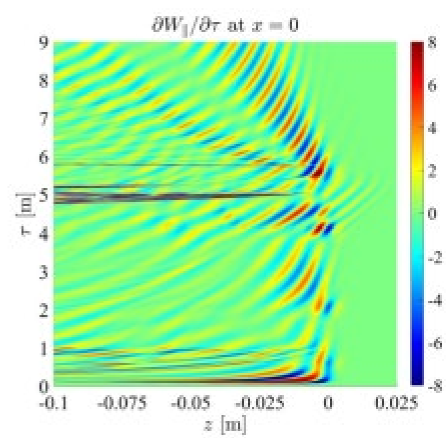
ELEGANT [3], BMAD [5], OCELOT [6]



Field-based Approach

- Uses a frequency-domain-based approach.
- Allows the computation of shielding.
- Not widely used or benchmarked (?)

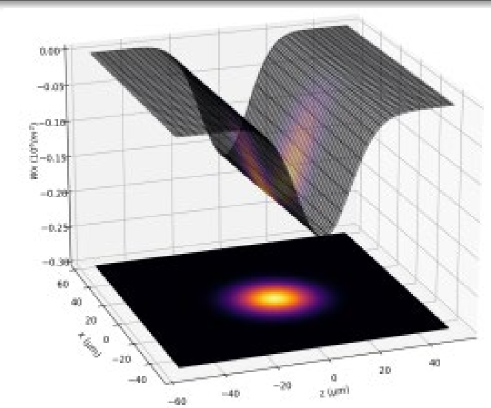
Agoh [7], Novokhatski [8], CSRDG [9]



2D – 3D Approach

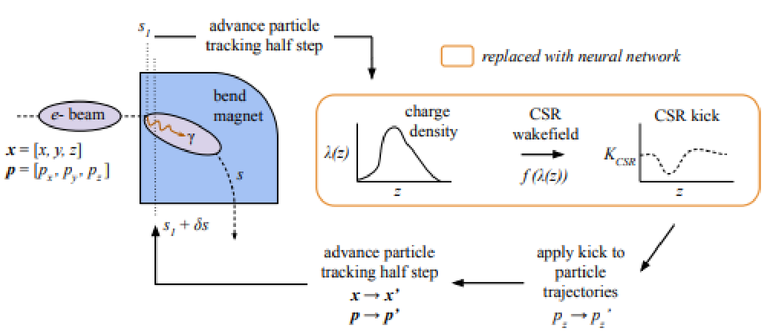
- A variety of methods are now available which take the transverse extent of the bunch into account.
- Some are more brute-force, others are based on Green's functions and FFT.

CSRTrack [10], GPT [11], CSR2D [12], CSR3D [13], LW3D [14], CoSyR [15], OpenCSR [16], Tang&Stupakov [17]



Neural Networks

- Data for CSR kicks generated using BMAD and fed into a NN solver [18]
- Achieves 10x speed improvement.



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CSR - Experiments

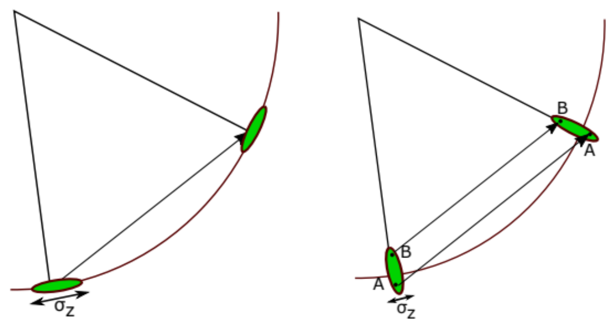
Emittance Growth

- For FELs, the most significant effects of CSR are on the transverse emittance.
- It was expected that the 1D CSR approximation would break down in extreme bunch compression scenarios [19].
- This was observed experimentally at FERMI as we approached maximum compression [20].
- The measured emittance diverged from the 1D simulation and agreed better with 2D-3D results.

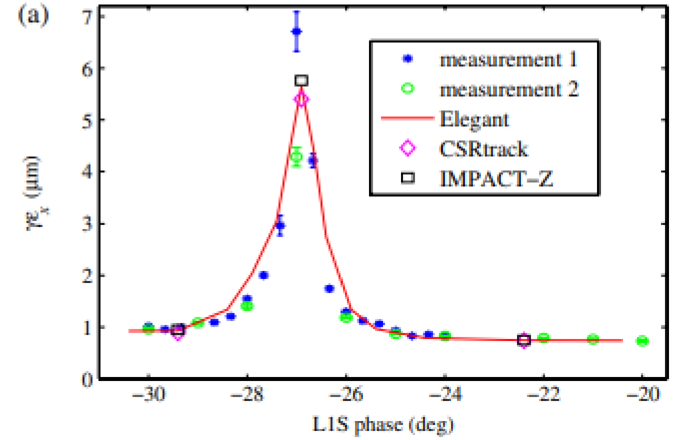
$$\Delta\epsilon_N^{\text{long}} = 7.5\times10^{-3}\frac{\beta_x}{\gamma}\left(\frac{r_e N L_b^2}{R^{5/3}\sigma_z^{4/3}}\right)^2,$$

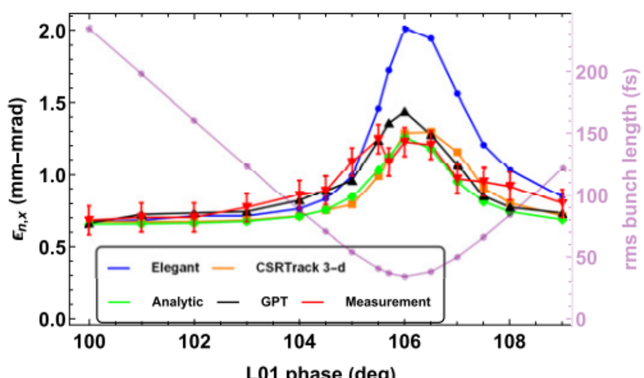
$$\Delta\epsilon_N \approx 2.5\times10^{-2}\frac{\beta}{\gamma}\left(\frac{N r_e L_b}{R\sigma_z}\right)^2.$$

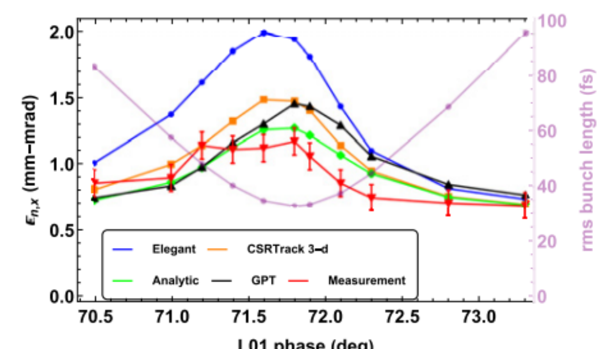
Potential deficiency in the 1D CSR model



Projected emittance as a function of compression factor at LCLS [21]







Projected emittance as a function of compression factor at FERMI [20]

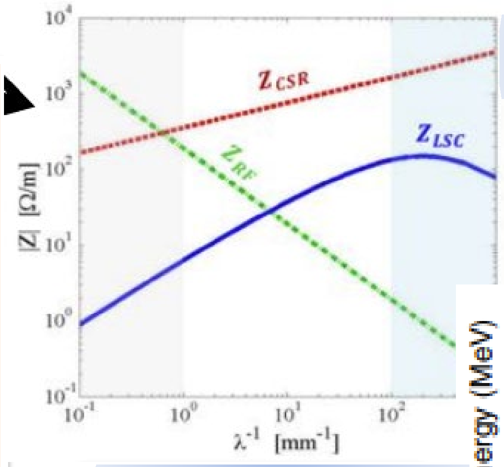
Summary

- The CSR models we have are reliable in terms of predicting emittance growth.
- Much work has been done in recent years to delve more deeply into simulating more realistic scenarios.
- Simulations are much faster than before!

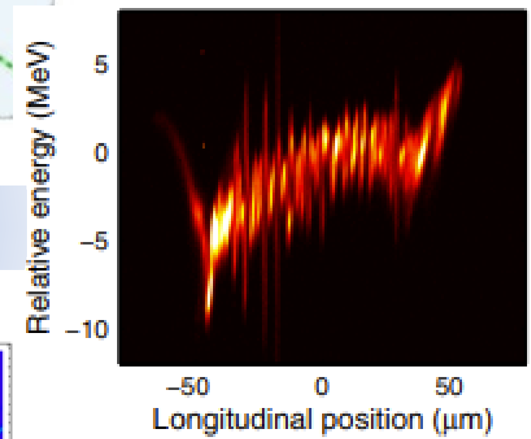
Microbunching Instability - Introduction

Causes and Consquences

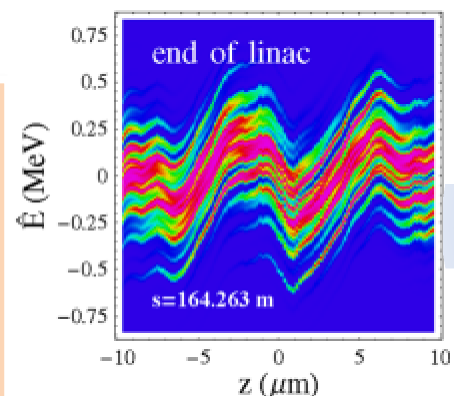
- Charged particle bunches are **not smooth** – imperfections in **PI laser pulse, cathode, shot noise**.
- These imperfections are amplified by **collective interactions** at characteristic frequencies [21 – 25].
- At the entrance to the FEL, the bunch longitudinal phase space can be **strongly modulated**.
- The FEL then loses **longitudinal coherence** [26, 27].



Impedances that give rise to microbunching [28].



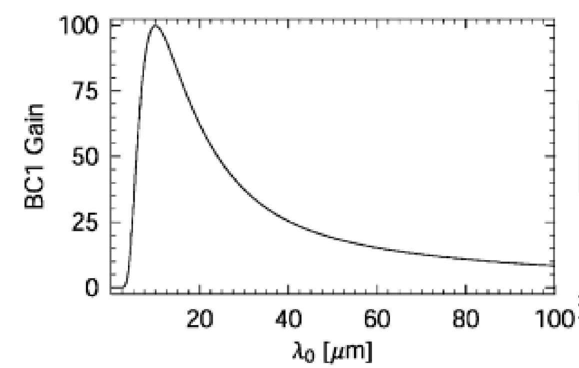
Microbunched longitudinal phase space [29]



Simulated longitudinal phase space [30]

Current Issues

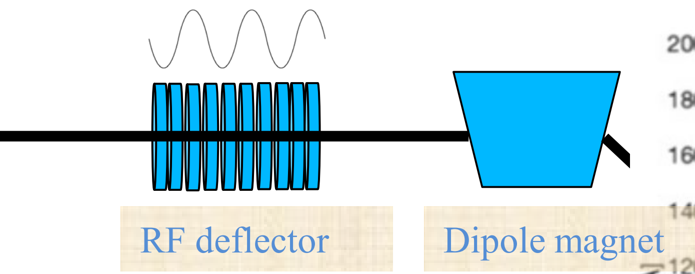
- MBI gain is strongly dependent on **initial conditions**, which are largely unknown.
- What is the best way to **measure** microbunching?
- How **accurate** are our **simulations**?
- How to **remove microbunching**?

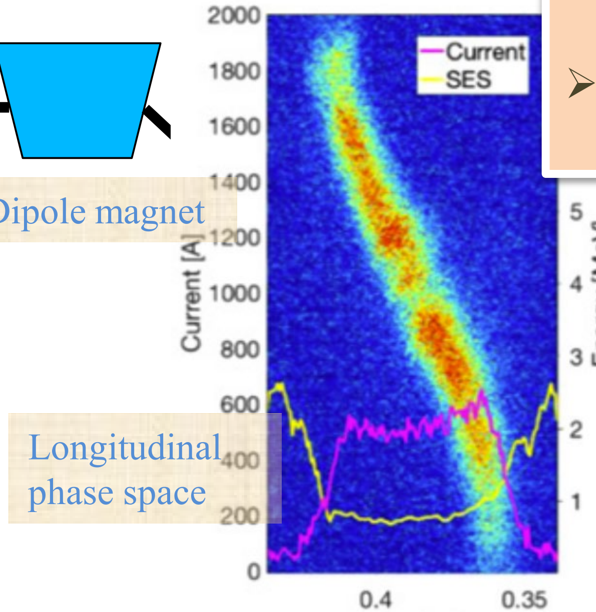


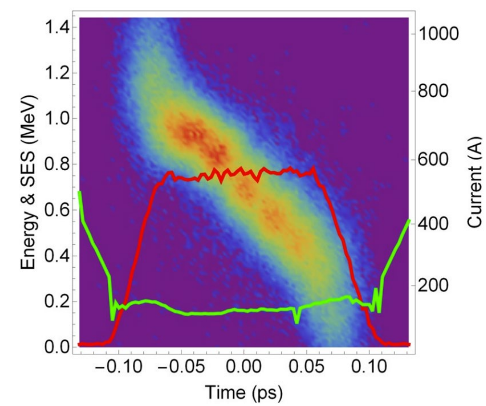
Theoretical microbunching gain [2]

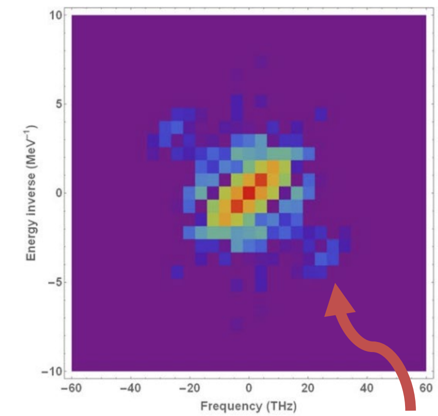
Direct Measurement – Transverse Deflector

- Streaking the beam transversely, then bending it with a dipole, gives a measurement of the longitudinal phase space.
- This allows us to measure the modulations directly in both **time and energy simultaneously** [31].



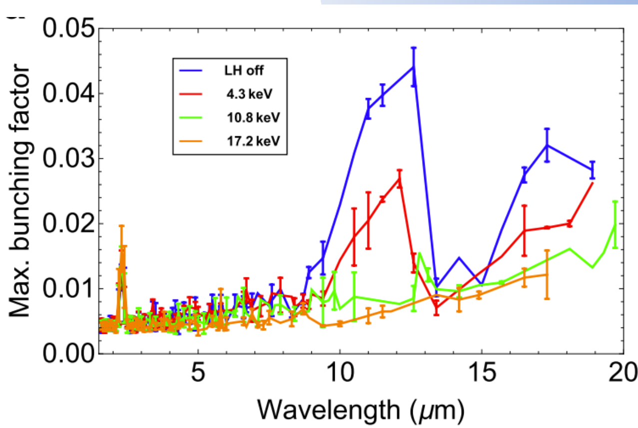


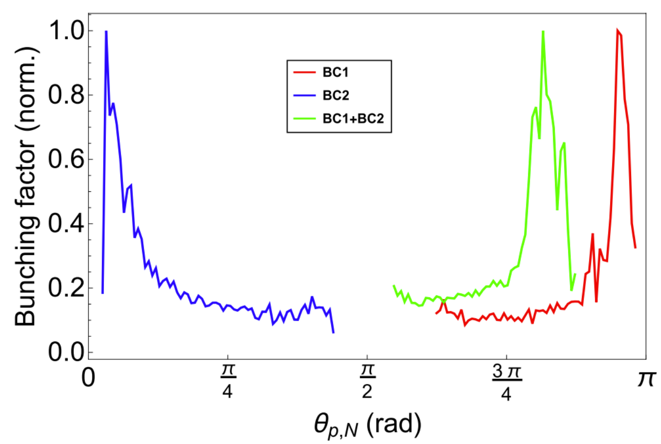




Microbunching is here in Fourier space!

Bunching factor (left) and plasma oscillation phase (right)





- This measurement method gives lots of detail, but the analysis is complicated.
- Alternatively, we can use the SPIR (see C. Spezzani's talk)

Simulating Microbunching

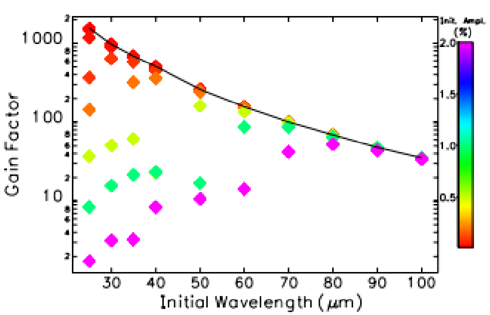
Macroparticle Simulations

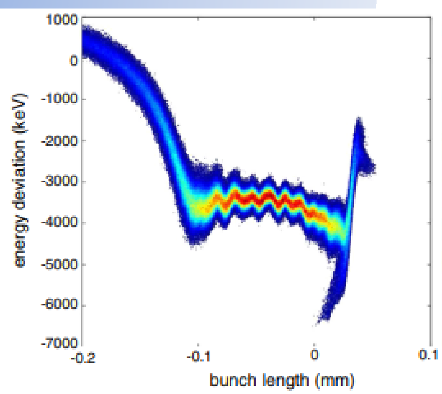
- Any code that can simulate collective effects can calculate microbunching gain.

Pros:
•Can be integrated into standard tracking routines.
•Allows for direct comparisons with measurements.

Cons:
•Numerical noise can have a strong effect.
•Non-physical input parameters.
•Significant computational requirements.

Simulated gain (left) [32] and longitudinal phase space (right) [33]





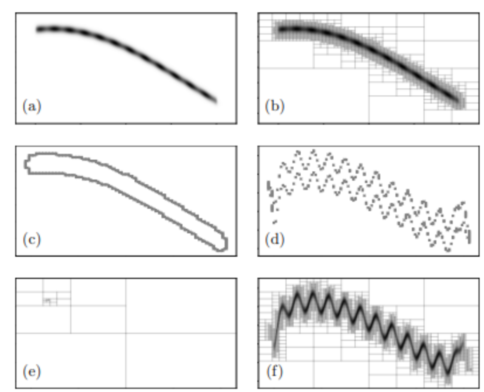
Semi-Analytic Methods

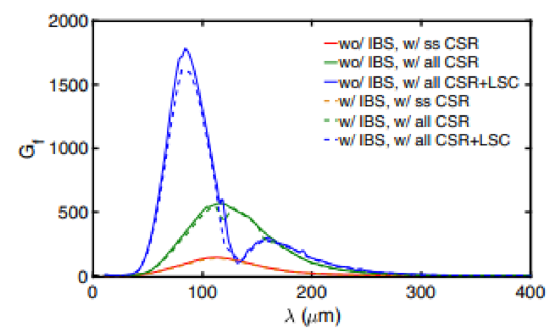
- Starting with the Vlasov formalism, it is possible to model the evolution of the beam as a result of collective effects.

Pros:
•Much faster evaluation than tracking codes.
•Less susceptibility to numerical effects.
•Impacts of individual effects is easier to isolate.

Cons:
•It is less clear how to connect these results to S2E simulations.

Results from Vlasov solvers [34, 35]





- How best to determine the impact of microbunching, and connect the simulations to real experimental data?
- How do these results impact our understanding of microbunching, and the design of future machines?
- Are we missing anything?

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Benchmarking Simulations

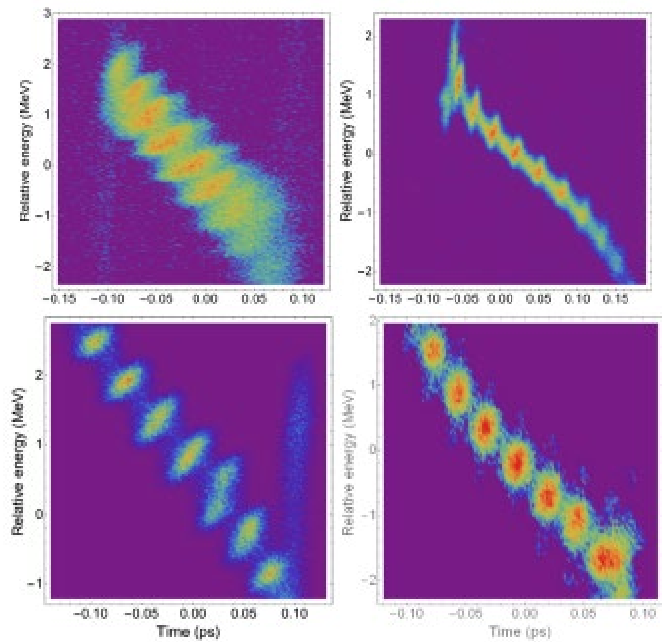
The model is pretty reliable!

The Problem(s)

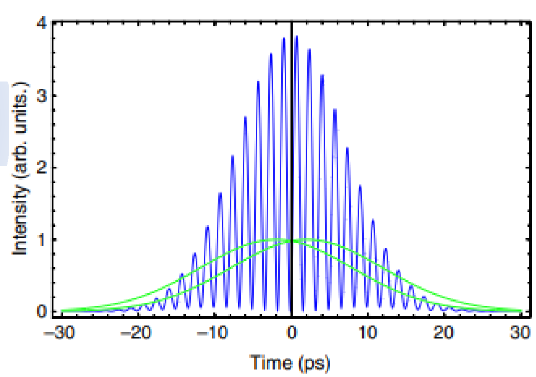
- Knowing how microbunching develops is strongly dependent on the initial conditions (slice energy spread, initial modulations), which we **can't measure**.
- Simulating microbunching requires numerical (non-physical) inputs – what are the correct settings?

A solution

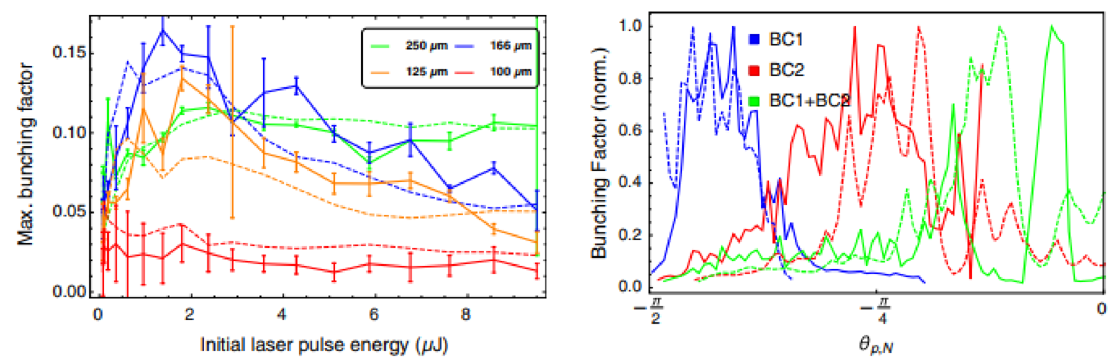
- Seed microbunching at a known wavelength and see how well the model matches the measurement.



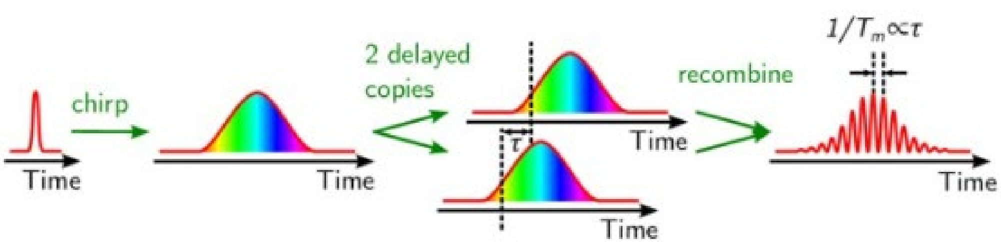
Measured (above) and simulated (below) longitudinal phase spaces with modulations seeded at 1.8 THz, compressed using BC1 (left) and BC2 (right) [37]



Modulated laser heater intensity profile



Measured (solid) and simulated (dashed) bunching factor (left) and plasma oscillation phase (right) as a function of LH energy for different modulation wavelengths.

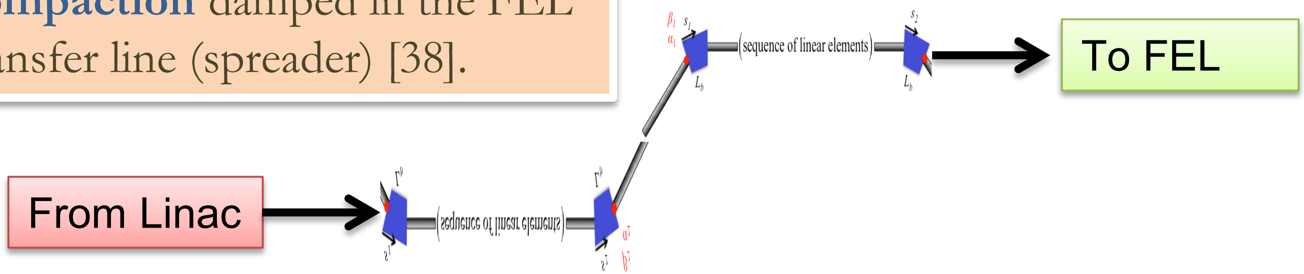


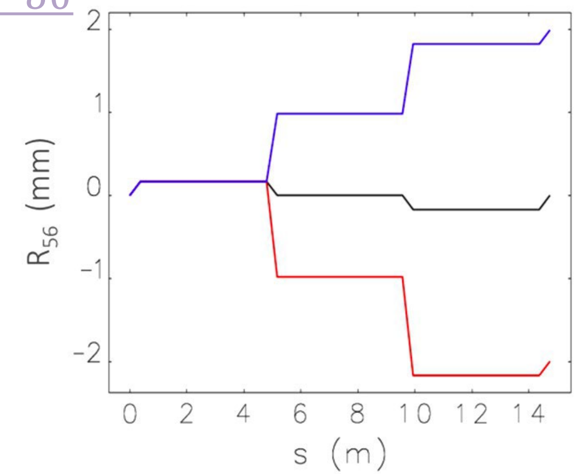
Chirped-pulse beating technique [36]

Damping Microbunching via Linear Optics Control

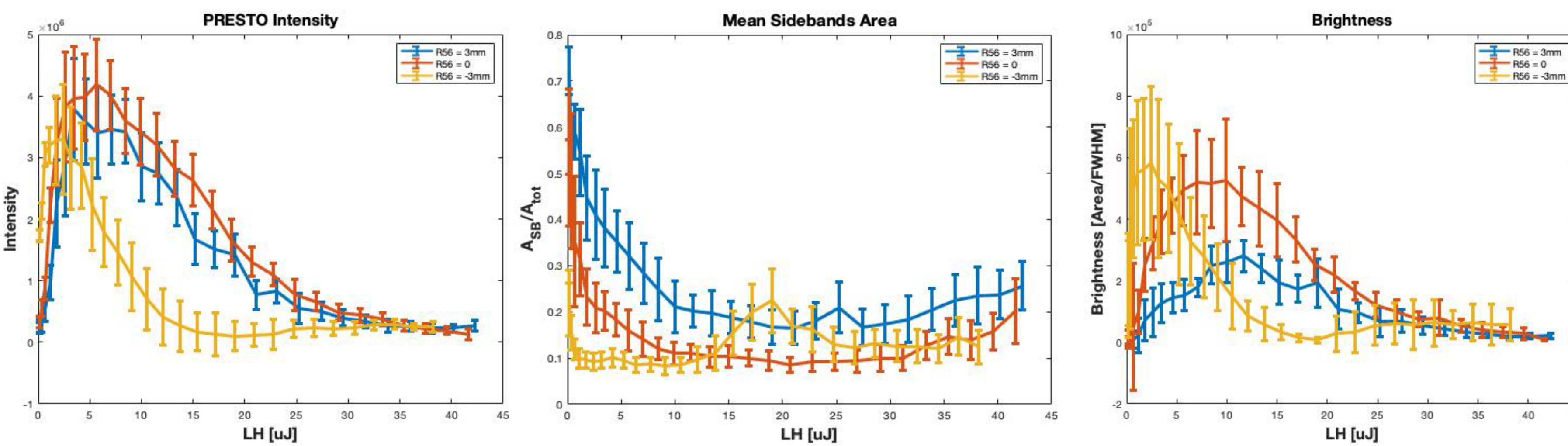
- The **final bunching factor** can be damped by the **momentum compaction** damped in the FEL transfer line (spreader) [38].

$$b_f(k,s) \propto e^{-\frac{k(s)^2 R_{56}^2(s)\sigma_{\delta 0}^2}{2}}$$





FEL performance for different values of R56 in the spreader [38]



- We will discuss optics-based alternatives to the laser heater here.
- See talk by P. Amstutz for details about laser heaters.

Damping Microbunching via Transverse Optics Control

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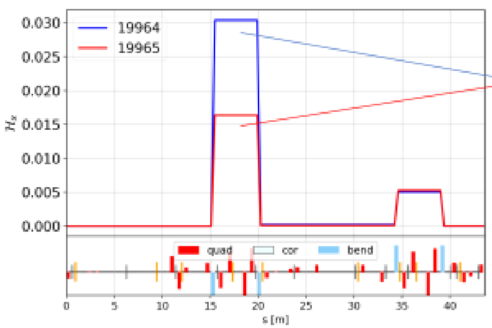
$$b_f(k,s) \propto e^{-\frac{k(s)^2 \mathcal{H}(s)\epsilon_{x0}}{2\gamma(s)}}$$

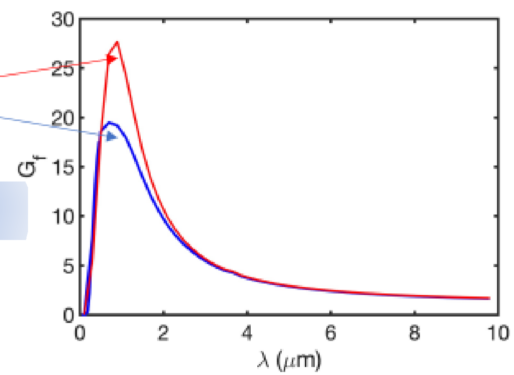
$$\mathcal{H}(s) = \frac{\gamma(s)}{\gamma_0}\frac{[\beta_{x0}R_{51}(s) - \alpha_{x0}R_{52}(s)]^2 + R_{52}(s)}{\beta_{x0}}$$

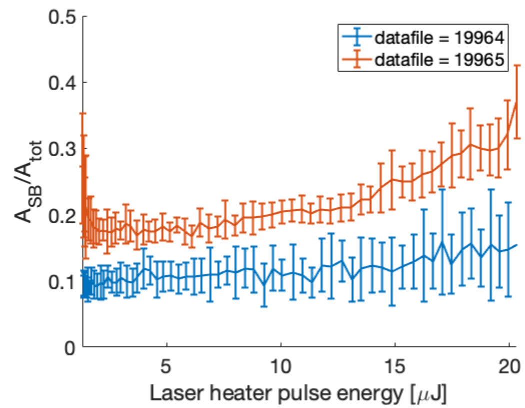
- On multiple occasions we have found configurations with different optics in the spreader leading to:
  - Reduced MBI signal on SPIR.
  - Cleaner FEL spectrum.

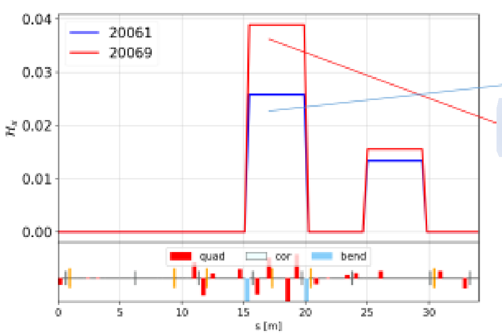
- The **final bunching factor** can be damped by the **dispersion invariant**



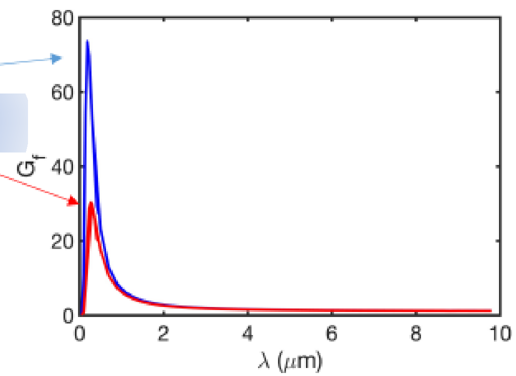
FEL1

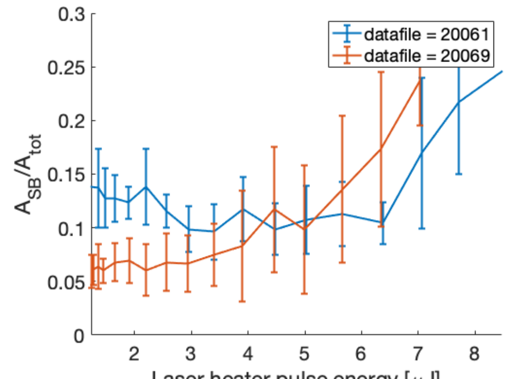






FEL2





Spreader H-functions for different optics

MBI gain in the spreader only (Vlasov solver)

FEL sideband area vs. LH pulse energy

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Conclusions

CSR

- The **limitations** of the 1D CSR model have been explored experimentally and in simulation.
- More stringent limits on transverse emittance require more **advanced models**.
- Recent developments have shown that it is possible to capture these complicated dynamics.

Next steps

- Investigate **new CSR models** to compare with **experimental data**.
- What are the **limits** of these new models?
- What is most **appropriate** to use for extreme/advanced compression schemes?
- Is emittance growth **the only way** of investigating CSR, or just the most practical?
- How best to compare **arc compression** with **chicane-like?**

Microbunching

- Microbunching has long been studied as a potential **show-stopper** to producing fully coherent FEL radiation.
- **Optics-based** alternatives to the laser heater show promise in **improving FEL performance**.
- **Other proposed** and **realised schemes** are out there!

Next steps

- Try to develop further optics-based schemes, (H-function, **IBS**) or alternatives (i.e. **TGU**, different **cathode** materials).
- Investigate new methods for diagnosing the instability (**Radon transform** of longitudinal phase space, **non-invasive SPIR**, …)
- Determine the **range of applicability** of macroparticle **simulations** and **analytic** methods.
- Is it possible in principle (or desirable) to characterise fully the **microbunching in a low-energy beam**?

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