High-resolution studies of microbunching phenomena in LCLS2

M. Venturini

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Not a boring machine:
LCLS2 as a “microbuncher” paradise

- Longitudinal Space Charge + z-Slippage = Microbunching instability
- Instability seeded by shot noise or other noise (e.g. in photo-cathode laser)
- Other micro-structures from beam/laser interaction in LH

Injector (velocity bunch compression)
Laser Heater (motion through chicane; Laser/beam interaction)
BC Chicanes (compression, dispersion)
Dogleg1 at entrance of bypass line (dispersion)
LTU sections -aka Dogleg2- (dispersion)
Method: PIC code

(Macro)particle simulations
- IMPACT Pic Code + Access to NERSC computing facilities
- One electron, One macroparticle
- 3D space charge (+ 1D CSR, rf wakes)

Two simulation approaches:
- *Machine section-by-section studies; Track idealized macroparticle distribution representing short section of physical bunch; Higher grid resolution, faster run turn-around.*

- *Cathode-2-undulator simulations of realistic whole beam (will not be shown here)*

Always try to make contact with analytical models when feasible
More on the code

- **IMPACT** = IMPACT-t (injector) + IMPACT-z (Linac)
  - written and maintained by J. Qiang (LBNL) et al.

- Optimized for heavy-duty multi-processor runs (NERSC);
- Efficient 3D Poisson Solver; 1D CSR; rf wakes

**100pC Beam @ Exit of injector**

- Uniform 3D grid (follows bunch compression, transverse beam breathing)
- Needed grid resolution can be demanding:
  - Eg. in injected beam, ~20 grid points to resolve 1μm -> 100k z-grid nodes needed for ~5mm beam

- s2e runs, Linac, ~1B macro particles,
  \[ n_x \times n_y \times n_z = 32 \times 32 \times 2048 \text{ grid,} \]
  take ~3 hours on 1000 processors; miss out some of the effects.
The laser heater doing its job

LH chicane

Longitudinal phase space at exit of chicane with randomized energy spread

Longitudinal phase space at exit of undulator showing modulation with $\lambda_L$ wavelength

5$\mu$m

Old (March 2014) baseline Lattice
A story of hidden correlations …

... but correlations are hiding in the $x'/z$ plane

no apparent correlations in $x/z$ plane at exit of chicane …

KV beam distribution for illustration
... $\pi/2$ phase-advance later

correlations have disappeared from the $x'/z$ plane ...

... but show up in the $x/z$ plane

3D space charge effects associated with microstructure heat the beam

Discovered during LCLS1 commissioning ("Trickle heating effect").
The ‘trickle’ heating & shot-noise seeded heating

- IMPACT simulation. **Idealized flat-top** beam with $I_0 = 12\,\text{A} \ (100\text{pC}\text{ bunch})$. Gaussian energy and transverse beam distribution.

- **3D space-charge effects** add to nominal LH-heating

- Anomalous heating **limits tuning range** of heater

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**Trickle heating effect for two choices of laser wavelengths ($Q = 100\text{pC}$)**

- **Nominal heating**
- **Anomalous heating** (baseline)
- **Required heating**

**Observed heating at 2 locations along lattice**

- @entrance of BC1 (trickle + shot-noise seeded heating)
- @entrance of L1 (trickle heating - mostly)

Injected warm beam: $\sigma_{E_0} = 2\text{keV}$
Heating due to shot-noise seeded microbunching

Microbunching induced by Laser Heater chicane causes energy modulation

Shot noise

Laser Heater chicane

Bunching at $>5 \times$ shot noise level

Accumulation of energy modulation at $\lambda \sim 2 \mu m$

Collimation Section

Long. phase space @ Entrance of BC1

Energy distribution

After removing chirp
**μBI** Gain curve through LH Chicane: choose $R_{56}$ to reduce instability

Note: gain curves based on simplified model excluding collective effects in chicane

Old LH chicane baseline $|R_{56}|$ close to worst...

Here, reducing (vs. increasing) $|R_{56}|$ is the more effective way to reduce gain

$$G \approx 4\pi \frac{I_0}{I_A} L_s \frac{|Z(k)|}{Z_0 Y_{BC}} |R_{56}| k e^{-(kR_{56}\sigma_\delta)^2/2}$$
We redesigned the LH chicane to have a smaller $|R_{56}|$

- Redesign chicane, keeping the same max $D_x = 7.5$ cm [lengthen drifts between 1-2 and 3-4 dipoles]

**Old baseline LHC** $|R_{56}| = 14$ mm

- $\theta_B = 100$ mrad
- $L_1 = 0.6$ m ($1^{st}$ to $2^{nd}$ bend drift)

**Redesigned LHC with** $|R_{56}| = 3.5$ mm

- $\theta_B = 24$ mrad
- $L_1 = 2.94$ m ($1^{st}$ to $2^{nd}$ bend drift)

Gain curve

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$\sigma_{E0} = 5$ keV
Macroparticle distributions (~1B) are created by IMPACT using a pseudo-random generator. Is this good enough?

- As of now, no evidence of problems, but one should run randomness tests to be sure
- Random numbers are for sale on [WWW.RANDOM.ORG](http://WWW.RANDOM.ORG) ...
LH Chicane with smaller $|R_{56}|$ does indeed reduce shot-noise seeded heating

Observed energy spread vs. Laser Pulse Energy

Old (March) Baseline
LH chicane with $R_{56} = -14mm$

Current Baseline
LH chicane $R_{56} = -3.5mm$

Note: here slice energy spread of injected beam $\sigma_{E0} \sim 0$

In modified LH chicane design trickle heating is somewhat larger at higher laser pulse energies (see next slide)
Trickle heating: Compare simulation with analytical model (Z. Huang) … and get reasonable agreement

Observed energy spread vs. Laser Pulse Energy

Old Baseline LH chicane ($R_{56} = -14\text{mm}$)
near entrance of L1; $\square$ 1030nm; $\diamondsuit$ 2keV; 80M macro p.

Current LH chicane ($R_{56} = -3.5\text{mm}$)
near entrance of L1; $\square$ 1030nm; $\blacktriangle$ 0.01keV

Trickle heating $\propto J_1(R_{56}k_L\delta_L)$
Further modification of LH chicane would almost eliminate trickle heating

- Trickle heating mostly gone
- Shot-noise induced $\mu B1$ heating remains small
- Drawbacks:
  - longer chicane (~12m)
Transport through doglegs/bypass greatly amplifies the microbunching instability

Macroparticle simulation of flat-top model beam with gaussian uncorrelated energy spread at exit of BC2 representing short section of $Q = 100pC$ bunch with Laser Heater turned on.

Microbunching on sub-μm scale develops through DL (entrance of bypass) and transport section between μ-wall and FEL.

*Correlated energy chirp removed
Problem starts with DL1: look at spectrum

Launch flat-top beam here


DL1 baseline

Current profile

Spectrum

No peak at $\lambda \sim 0.1 \mu m$

Single shot

$\theta = 0.024 \text{ rad}$

$\theta = -0.024 \text{ rad}$

$R_{56} = +200 \mu m$

Observe beam here

$|R_{56}|$ - equiv. short chicane replacing DL1

1D linear model

Avg. over 4 shots

BC2
Aside on 1D vs. 3D
(and fine print too fine to read)

- Linear theory of gain with 1D LSC model predicts essentially the same spectrum through DL1 as through a (short) 4-bend chicane with identical $|R_{56}|$.
- Theory doesn’t reproduce spectrum observed at exit of Dogleg (DL1) very well.

We are still baking the cookies – not ready for last word.

- Limitation of the 1D LSC model within dogleg?

- Why the smoothing at higher spatial frequencies?
  - Longitudinal mixing induced by finite transverse emittance:
    - Beam size in dogleg: $\sigma_{x} \sim 30 \mu m$
    - $\sigma_{x} \sim 1.2 \mu rad$
    - Dogleg dipoles: $\theta = 0.024 \, rad$, $L_{BRB} = 1m$

  Smoothing from finite transverse beam size: $\Delta z \sim R_{51} \sigma_{x} = \theta \sigma_{x} \sim 0.7 \mu m$
  finite angular spread: $\Delta z \sim R_{52} \sigma_{x'} = \frac{L_{BRB}}{2} \theta \sigma_{x'} \sim 0.015 \mu m$

- As the beam exits the 2nd bend in dogleg high-frequency components of energy modulations accrued within DL should be washed away and we would expect no additional contribution to the bunching observed at exit of DL1 (effectively, it is as if LSC was not active in DL; as predicted by 1D linear theory)

- However: if LSC 3D effects were important bunching induced by space charge within chicane may not be as strongly suppressed as expected based on a 1D model (Ref. experience with OTR measurements in LCLS1 downstream of DL at injector during commissioning, D. Ratner et al.)

- Are we in 3D regime? $\frac{kr_{b}}{\gamma} \sim 0.4$ for $\lambda = 0.1 \mu m$. Is this large enough to claim 3D effects are important?
Non-local $R_{56}$ compensation?

**DL1 baseline**

$R_{56} = +100 \mu m$

**Baseline DL1 + equivalent chicane**

$R_{56} = -200 \mu m$

$\theta = 0.014 \text{ rad}$

Not good ...
Try local $R_{56}$ compensation

$R_{56} = -100\mu m$

$R_{56} = +100\mu m$

BC2

DL1 baseline

Baseline DL1 +2-compensating chicanes
Make all main doglegs locally isochronous (to HXR)

Non-local compensation of $R_{56}$ not as effective.
Alternate local compensation schemes may be possible
Robustness against jitters, errors?
Effect on transverse emittance?
Delaying compression to exit of bypass would also be a way to reduce microbunching

* Correlated energy chirp removed
Conclusions

- The Laser Heater: watch out what you ask for!
  - Anomalous heating (trickling, microbunching)

- Long transport lines are potential trouble makers.
  - Making the transport lines locally isochronous as much as possible should fix the problem.

- After having taken the pain to try to avoid it, Could we use the $\mu BI$ for something good?
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