Summary of the IMPACT Simulation of the LCLS-II Beam Delivery System

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IMPACT: Integrated Map and PArticle Tracking Code

H = H_{ext}

Split-Operator Method

H = H_{ext} + H_{sc}

M = M_{ext}

M(t) = M_{ext}(t/2) M_{sc}(t) M_{ext}(t/2) + O(t^3)

M = M_{sc}

Magnetic Optics

Multi-Particle Simulation

(arbitrary order possible via Yoshida)
IMPACT: Integrated Map and Particle Tracking Code

- Some key features include:
  - Serial and massive parallelization
  - IMPACT-T + IMPACT-Z
  - Detailed 3D RF accelerating and focusing model, dipole, solenoid, multipole, …
  - Multiple charge states, multiple bunches
  - 3D space-charge effects
  - Structure + resistive wall wakefields
  - Coherent synchrotron radiation (CSR)
  - Incoherent synchrotron radiation (ISR)
  - Gas ionization
  - Photo-electron emission
  - Ion beam formation
  - Machine errors and steering

IMPACT has been used by researchers at more than 30 institutes and universities
Beta Function Evolution: IMPACT vs. Elegant

Very good agreement between the IMPACT and the Elegant!
Physical Models Used in the IMPACT Simulation

- Simple RF cavity model
- $5^{th}$ order transfer map of dipole
- Linear map of dipole with individual energy dependent focusing
- 3D space-charge
- Longitudinal structure wakefield
- 1D CSR
- ISR in dipole
- 1 electron – 1 macroparticle
Large Number of Macroparticles Needed to Accurately Model Shot Noise
Map of microbunching phenomena along lattice

- **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)
The ‘trickle’ heating effect induced by laser-beam interaction

- **LH undulator**

- **Trickle heating effect for two choices of laser wavelengths** ($Q = 100pC$)
  - $\lambda_L = 1500\,\text{nm}$
  - $\lambda_L = 1020\,\text{nm}$ (baseline)
  - Required heating
  - Nominal heating

- **μ-structure appears downstream of LH**

- **Impacted simulation. Idealized flat-top beam with $I_0 = 12A$ (100pC bunch). Gaussian energy and transverse beam distribution.**

- Excessive anomalous heating would limit tuning range of heater

- Simulations requires very high mesh resolution
LH Chicane was redesigned to reduce shot-noise seeded heating

Observed energy spread vs. Laser Pulse Energy

Old (March ‘14) Baseline, Q=100pC
LH chicane with $R_{56} = -14\text{mm}; L = 4\text{m}$

Current Baseline (showing improvement)
LH chicane $R_{56} = -3.5\text{mm}; L = 8\text{m}$

$\sigma_{E0} \sim 0$
Follow the beam to the FEL and find spectacular bunching.

Start simulation with smooth beam model at exit of BC2.

Beam as observed at HXU FEL is strongly microbunched.

- **Correlated energy chirp removed**

[[Graph showing current profile and long phase space]]

- **Flat-top model beam with gaussian uncorrelated energy spread**
  - Represents short section of $Q = 100pC$ bunch (laser heater on.)

- Strong microbunching on **sub-μm scale**

*Correlated energy chirp removed*
Longitudinal Phases and Current Profiles

After BC2

Entrance to Undulator
Method appears to be highly effective

- Delaying compression to exit of bypass could also be a way to reduce microbunching, may have drawbacks
- Is everything all right, then? Not quite …

*Correlated energy chirp removed*
Longitudinal Phases and Current Profiles with and without Compensation Chicanes

➢ compensation chicanes help reduce microbunching
The $\mu BI$ strikes back ...

The observed gain is due to **transverse** space-charge (TSC) in the doglegs & **longitudinal** space charge (LSC) elsewhere.

- Re-tuning the compensating chicanes helps (next slide)
Compensation Chicane Optimization (100 pC HXR)

- 15-25% over compensation significantly reduces microbunching

Nominal setting = 0
Compensation Chicane Optimization (100 pC SXR)

- 10-25% over compensation significantly reduces microbunching
Compensation Chicane Optimization (300 pC HXR)

- 10-20% over compensation significantly reduces microbunching
Compensation Chicane Optimization (300 pC SXR)

- 10-20% over compensation significantly reduces microbunching
Transverse RMS Sizes Evolution
(before optimization)

Transverse space charge causes significant envelope mismatch
Transverse RMS Sizes Evolution
(after optimization including space-charge effects)

- optimization including SC improves the rms beam size matching

optimized 8 quads
Phase Plot w/o Quad. Optimization

after LH

before BC1
Center Slice Emittance Evolution w/o Quad. Optimization

slice emittance growth in two regions:

after LH

after BC1
Final Longitudinal Phase Spaces and Current Profiles (20 pC) (with and without BC3)

No BC3

> 15 MeV

with BC3
Final Current Profiles with BC 3 Tuning (100 pC)

Not significant improvement with BC3.
Summary of Modifications

Laser heater: old R56 - 14 mm, L = 4 m
   new R56 - 3.5 mm, L = 8 m

Quads before LH (k1):
   -10.53895 -> -10.780666; 5.518705 -> 5.870817;
   10.66611 -> 10.81638;
   -11.70568 -> -11.851849

Quads after LH (k1):
   -8.640766 -> -8.611757; 6.584925 -> 6.4575648

Add BC3 before spreader for 20 pC: R56 = -26.6 mm, L = 23 m

Compensation chicanes: All bending angles increases by 15%
## Summary of Performance

<table>
<thead>
<tr>
<th>IMPACT Studies</th>
<th>$I_{\text{peak}}$ (A)</th>
<th>$\sigma_E$ (keV)</th>
<th>Proj. $\varepsilon_x / \varepsilon_y$ (mm-mrad)</th>
<th>Slice $\varepsilon_x / \varepsilon_y$ (mm-mrad)</th>
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<tbody>
<tr>
<td>20 pC</td>
<td>299</td>
<td>446</td>
<td>0.21 / 0.13</td>
<td>0.16 / 0.10</td>
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<tr>
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<td>294</td>
<td>444</td>
<td>0.23 / 0.12</td>
<td>0.15 / 0.10</td>
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<tr>
<td>100 pC</td>
<td>760</td>
<td>480</td>
<td>1.05 / 0.51</td>
<td>0.34 / 0.43</td>
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<td>755</td>
<td>592</td>
<td>3.5 / 0.44</td>
<td>0.34 / 0.42</td>
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<tr>
<td>300 pC</td>
<td>892</td>
<td>468</td>
<td>1.28 / 0.94</td>
<td>0.64 / 0.52</td>
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<tr>
<td></td>
<td>921</td>
<td>529</td>
<td>1.21 / 0.90</td>
<td>0.56 / 0.53</td>
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</table>
Next Step of IMPACT Simulation

- Optimize SXR beam line for 100 pC
- Optimize 20 pC w/o BC3
- full set of runs for 20, 100, 300 pC to HXR/SXR
- Start-to-end simulations using new shorter injector layout settings.
- Search for a 100 pC (HXR) + 300 pC (SXR) simultaneous operation mode using two independent BCs in the LTU lines.
- Investigate and understand transverse beam emittance growth.
- ‘Very-high’ mesh resolution in s2e simulations
Backup Slides
Final Longitudinal Phase Spaces and Current Profiles (100 pC)

HXR

SXR
Projected and Center Slice Emittance Evolution (100 pC HXR)
Final Longitudinal Phase Spaces and Current Profiles (300 pC)
Final Longitudinal Phase Spaces and Current Profiles (20 pC)
<table>
<thead>
<tr>
<th>20 pC</th>
<th>Phase (deg)</th>
<th>Voltage (MV)</th>
<th>Grad (MV/m)</th>
<th>No. modls</th>
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<tbody>
<tr>
<td>L1</td>
<td>-22.4526</td>
<td>226.321</td>
<td>13.6306</td>
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<tr>
<td>HL</td>
<td>-157.383</td>
<td>64.1</td>
<td>11.5788</td>
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<tr>
<td>L2</td>
<td>0</td>
<td>1350</td>
<td>13.551</td>
<td>12</td>
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<td>L3</td>
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<td>2402.09</td>
<td>14.4671</td>
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<table>
<thead>
<tr>
<th></th>
<th>(\theta (\text{rad}))</th>
<th>(R56 (\text{m}))</th>
<th>(E (\text{MeV}))</th>
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<tbody>
<tr>
<td>BC1</td>
<td>0.102687</td>
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<tr>
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<td>0.0</td>
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<tr>
<td>BC3</td>
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<td>100 pC</td>
<td>Phase (deg)</td>
<td>Voltage (MV)</td>
<td>Grad (MV/m)</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>--------------</td>
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<tr>
<td>L1</td>
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<td>14.5152</td>
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<td>0</td>
<td>2441.74</td>
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</tr>
<tr>
<td></td>
<td>θ (rad)</td>
<td>R56 (m)</td>
<td>E (MeV)</td>
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<tr>
<td>BC1</td>
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<tr>
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<tr>
<td>300 pC</td>
<td>Phase (deg)</td>
<td>Voltage (MV)</td>
<td>Grad (MV/m)</td>
</tr>
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<td>--------</td>
<td>-------------</td>
<td>--------------</td>
<td>-------------</td>
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<tr>
<td>L1</td>
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<tr>
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<tr>
<td>θ (rad)</td>
<td>R56 (m)</td>
<td>E (MeV)</td>
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<td>BC2</td>
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At entrance of DL1 bunch has still a substantial energy chirp left over from compression. ‘dechirping’ is completed by resistive-wall wake in bypass line.

\[ \delta_c \approx h_1 z \]

Energy chirp + dogleg \( T_{566} \) is effective \( R_{56}^{\text{eff}} \approx 2T_{566}h_1 z \approx 100\,\mu\text{m} \) (at \( z = 10\,\mu\text{m} \))

Away from bunch center effective \( R_{56}^{\text{eff}} \) is comparable in magnitude to DL1 \( R_{56} \)