Status of Start-to-End Efforts Towards a Conceptional CW XFEL

Exploring the qualities of e-bunches (from a SRF-gun based CW injector) before undulators

Ye Chen & Martin Dohlus
TEMF-DESY Collaboration Meeting (virtual), 2.11.2020

Thanks to co-workers:
Igor Zagorodnov, Frank Brinker, Dmitry Bazyl, Sergey Tomin, Sascha Meykopff, Torsten Limberg, Winfried Decking , Elmar Vogel, Evgeny Schneidmiller & many other co-workers from PITZ MPY, MXL & MSL

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Background

- ✓ **R&D activities towards a CW XFEL under continuous reviews of DESY Machine Advisory Committee**
  - → Not only about a CW injector
  - → But also S2E beam dynamics studies (Injector to Undulator)

- ✓ **Forward-looking guidance (2014)**

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 768, 21 December 2014, Pages 20-25

Prospects for CW and LP operation of the European XFEL in hard X-ray regime

R. Brinkmann, E.A. Schneidmiller, J. Sekutowicz, M.V. Yurkov

Show more

https://doi.org/10.1016/j.nima.2014.09.039

The European XFEL will operate nominally at 17.5 GeV in SP (short pulse) mode with 0.65 ms long bunch train and 10 Hz repetition rate. A possible upgrade of the linac to CW (continuous wave) or LP (long pulse) modes with a corresponding reduction of electron beam energy is under discussion for many years. Recent successes in the dedicated R&D program allow to forecast a technical feasibility of such an upgrade in the foreseeable future. One of the challenges is to provide sub-Ångström FEL operation in CW and LP modes. In this paper we perform a preliminary analysis of a possible operation of the European XFEL in the hard X-ray regime in CW and LP modes with electron energies of 7 GeV and 10 GeV, respectively. We consider lasing in the baseline XFEL undulator as well as in a new undulator with a reduced period. We show that, with reasonable requirements on electron beam quality, lasing on the fundamental will be possible in the sub-Ångström regime. As an option for generating brilliant photon beams at short wavelengths we also consider harmonic lasing that has recently attracted a significant attention.

Background (cont'd)

- ✓ **R&D activities regarding choices of the CW gun in light of S2E simulation results**
  - → Performance of various CW injectors in S2E beam dynamics

Choice of the gun for CW operation of the European XFEL

Igor Zagorodnov and Martin Dohlus
DESY, Hamburg

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S2E with OCELOT

SRF-gun based: 100 pC, 7 GeV, ~5 kA, ~0.7 µm (partially optimized)

100 pC, 4 GeV, ~1.4 kA, ~0.5 µm

✓ **International efforts in CW regime:**

LCLS-II Technical Note

60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources FLS2018, Shanghai, China JACoW Publishing
ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP1WA02

THE LCLS-II-HE, A HIGH ENERGY UPGRADE OF THE LCLS-II*

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Abstract

The LCLS-II is a CW X-ray FEL covering a photon spectral range from 200 to 5,000 eV. It is based on a 4 GeV SRF linac installed in the 1st km of the SLAC linac tunnel. This paper will describe a high energy upgrade, referred to as the LCLS-II-HE, which will increase the beam energy to 8 GeV and the photon spectral range to 12.8 keV; this range may be extended through 20 keV with improvements of the electron injector and beam transport. The LCLS-II-HE received the US DOE CD-0 approval, Mission Need, and has developed a CDR in support of a CD-1 review scheduled for summer 2018.

portunities identified in the latest report from the Basic Energy Sciences Advisory Committee (BESAC) [4], and will provide detailed insight into the behavior of complex matter, real-world heterogeneous samples, functioning assemblies, and biological systems on fundamental scales of energy, time, and length. The LCLS-II High Energy Upgrade (LCLS-II-HE) is a natural extension to LCLS-II, extending the high-repetition-rate capabilities into the critically important "hard X-ray" regime (spanning from 5 keV to at least 12.8 keV and potentially up to 20 keV) that has been used in more than 75% of the LCLS experiments to date.

LCLS-II Beam and FEL Performance Based on Start-to-End Simulations Using a Gaussian-profile injector Laser

LCLS-II-TN-20-03

6/5/20 **S2E with various tools**

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SLAC, Menlo Park, CA 94025, USA
J. Qiang **S2E with IMPACT**
LBNL, Berkeley, CA 94720, USA

Outline

- Motivation & Goals
- SRF injector optimization (D.Bazyl)
- RF energy gain budgets in CW regime (with inputs from E.Vogel)
- Accelerator S2E simulation capabilities (injector → undulator)
  - ✓ OCELOT
  - ✓ IMPACT-Z
- Summary & Outlook
- Backup slides
  - ✓ SASE simulations

Motivation & Goals

- **Injector optimization**

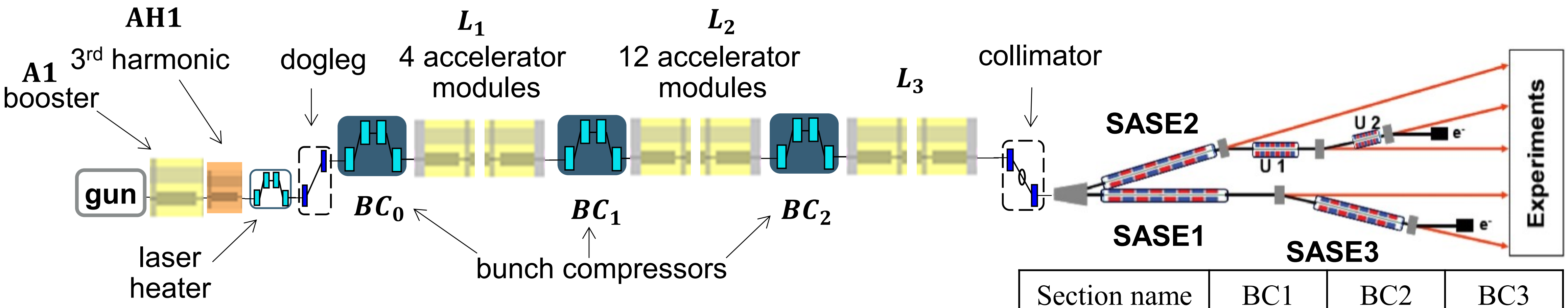
- **Capability studies** of conserving electron bunch qualities (from injector) through S2E beam dynamics simulations while compressing the bunch to reasonably high peak currents

- **Finer S2E investigations** in presence of collective effects, including particularly e.g. **micro bunching**

- Exploring **lasing performance** with optimized electron bunches before undulators

XFEL machine configuration

W. Decking et al, A MHz-repetition-rate hard X-ray free-electron laser driven by a superconducting linear accelerator, Nat. Photonics14, 391 (2020)



Section name	BC1	BC2	BC3
|r56|, mm	30-90	20-80	10-60

CW machine configuration staying same for current simulation studies

- **a high harmonic module** linearizing the longitudinal phase space
- **three bunch compressors** compressing the bunch to several kAs
- **design optics** providing a special phase advance between bunch compressors to reduce CSR

Energy gain budget in CW regime

- **First evaluation (E. Vogel):**
  - **16 MV/cavity** for 1.3 GHz
  - **4 MV/cavity** for 3.9 GHz
  - Beam energy at CW injector linac exit: **90 to 110 MeV**
  - Beam energy at BC1: **500 MeV**
  - Beam energy at BC2: **2 GeV**
  - Beam energy at exit of L3 (25 + 3 RF stations with 32 cavities each): **8 to 9 GeV**

- **A preliminary S2E energy profile for simulations**

  →110/500/2000/8000 MeV

- **A general optimization goal at a suitable S2E working point**

  → reasonably conserved central slice emittance, 4-5 kA peak current & smooth profile, reasonable slice energy spread before undulators (2-3 MeV)

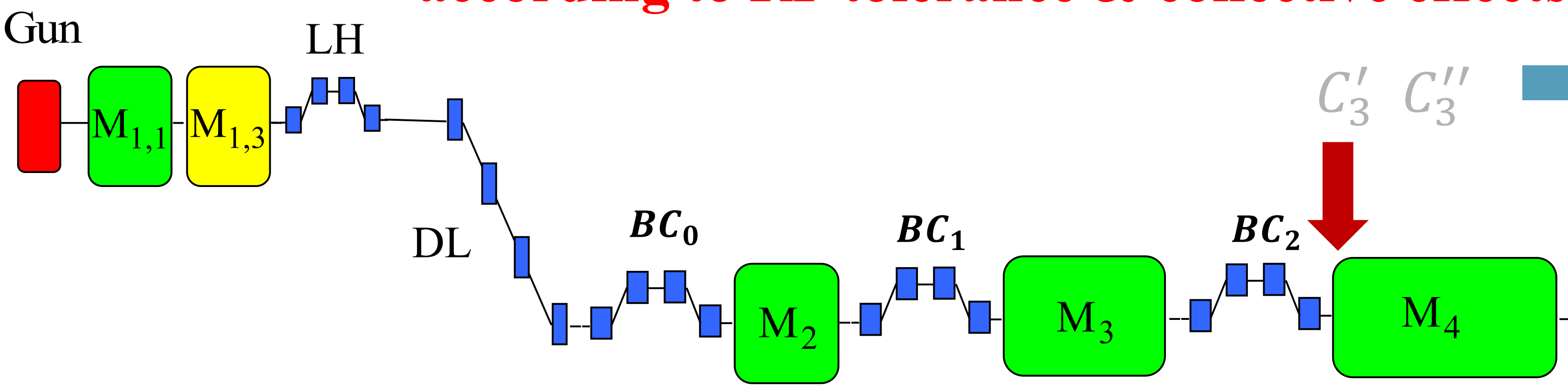
S2E beam dynamics with OCELOT

→ find proper working points / conditions for beam acceleration, transport & compression

→ to have stable compression
→ to obtain required bunch qualities before undulators
→ to generate SASE in hard X-ray regime

Longitudinal beam dynamics optimization

Multi-parametric optimization
according to RF tolerance & collective effects



the first and the second derivatives of the global compression

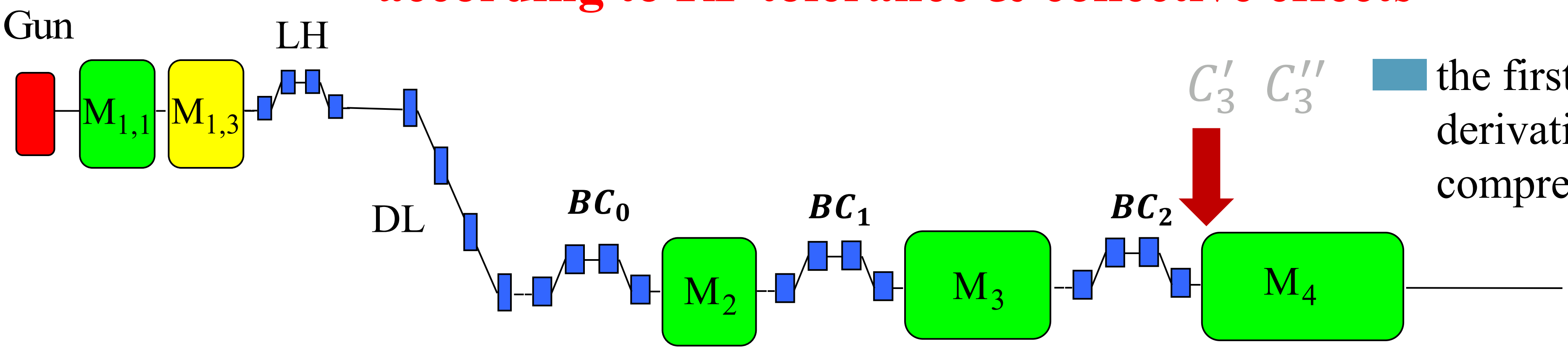
energy in BC:	E_1 = **110 MeV**	E_2 = **500 MeV**	E_3 = **2000 MeV**
deflecting radius:	$r_{56,1} = ?$	$r_{56,2} = ?$	$r_{56,3} = ?$
compression factor:	C_1 =?	C_2 =?	$C_3 = I_{\mathrm{final}}/I_{\mathrm{gun}}$

→ Searching for an optimal choice of parameters under technical constraints

e.g. E1/E2/E3→C3→C3′→r1→C1/C2/r2/r3→C3″

Longitudinal beam dynamics optimization

Multi-parametric optimization
according to RF tolerance & collective effects



the first and the second derivatives of the global compression

energy in BC: $E_1 = \mathbf{110\ MeV}$ $E_2 = \mathbf{500\ MeV}$ $E_3 = \mathbf{2000\ MeV}$

deflecting radius: $r_{56,1} = ?$ $r_{56,2} = ?$ $r_{56,3} = ?$

compression factor: $C_1 = ?$ $C_2 = ?$ $C_3 = I_{\text{final}}/I_{\text{gun}}$

→ Searching for an optimal choice of parameters under technical constraints

→ Final bunch length & peak current sensitive to energy chirp, thus to RF parameters

Longitudinal beam dynamics optimization (cont'd)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 024401 (2019)

Accelerator beam dynamics at the European X-ray Free Electron Laser

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(Received 10 October 2018; published 13 February 2019)

$A(\boldsymbol{x}) = \boldsymbol{f},$

$\boldsymbol{f} = (E_1^0, E_2^0, E_3^0, Z_1, Z_2, Z_3, Z_3', Z_3''),$ → BD parameters

$\boldsymbol{x} = (X_{11}, Y_{11}, X_{13}, Y_{13}, X_2, Y_2, X_3, Y_3)$ → RF parameters

$\boldsymbol{x}_0 = A_0^{-1}(\boldsymbol{f})$ → analytical

tracking

$\boldsymbol{x}_n = A_0^{-1}(\boldsymbol{g}_n), \quad \boldsymbol{g}_n = \boldsymbol{g}_{n-1} + \lambda[\boldsymbol{f} - A(\boldsymbol{x}_{n-1})], \quad n > 0,$

$\boldsymbol{g}_0 = \boldsymbol{f}, \quad \boldsymbol{x}_0 = A_0^{-1}(\boldsymbol{f}).$ → iterative algorithm

→ **Searching suitable RF parameters *x* to produce desired compression scheme *f***

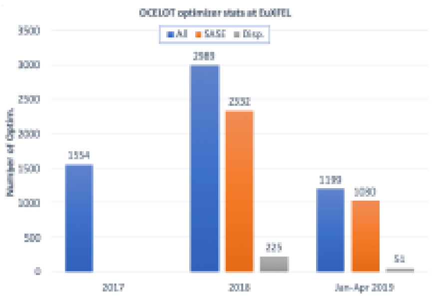
- → **Mapping RF parameters into longitudinal BD parameters**
- → **Realized by tracking program**

A simulation toolkit: OCELOT

OCELOT structure

Courtesy: Sergey Tomin

- Everything in **Python**. Focus on simplicity. Implement only physics
- Open source (On GitHub **https://github.com/ocelot-collab/ocelot**)

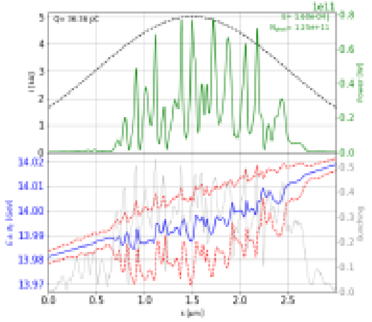


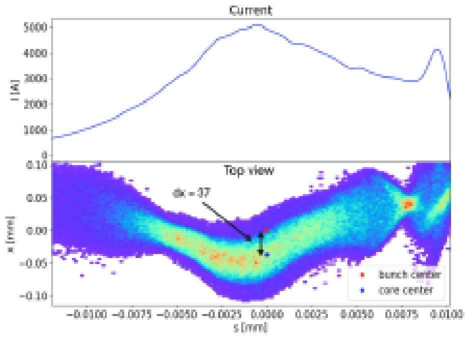
Data sets

Photon field simulation
- FEL simulations (genesis)
- Spontaneous radiation (ocelot)
- Wavefront propagation
- FEL estimator

Charged Particle Beam Dynamics (CPBD) module (linacs, rings)

Online beam control
- Orbit correction
- Adaptive FB
- Optimizer





OCELOT
- 3D Space Charge
- 3D wakefields
- 1D CSR
- particle motion with transport matrices of second order
- RF cavity with Rosenzweig-Serafini model
- Chamber with wakes

An iterative algorithm for searching RF parameters implemented in OCELOT

S.Tomin, I.Agapov, M.Dohlus, I.Zagorodnov, *Ocelot as framework for beam dynamics simulations of x-ray sources, in Proceedings of IPAC 2017, WEPAB031*

A fast estimation for S2E beam dynamics in OCELOT

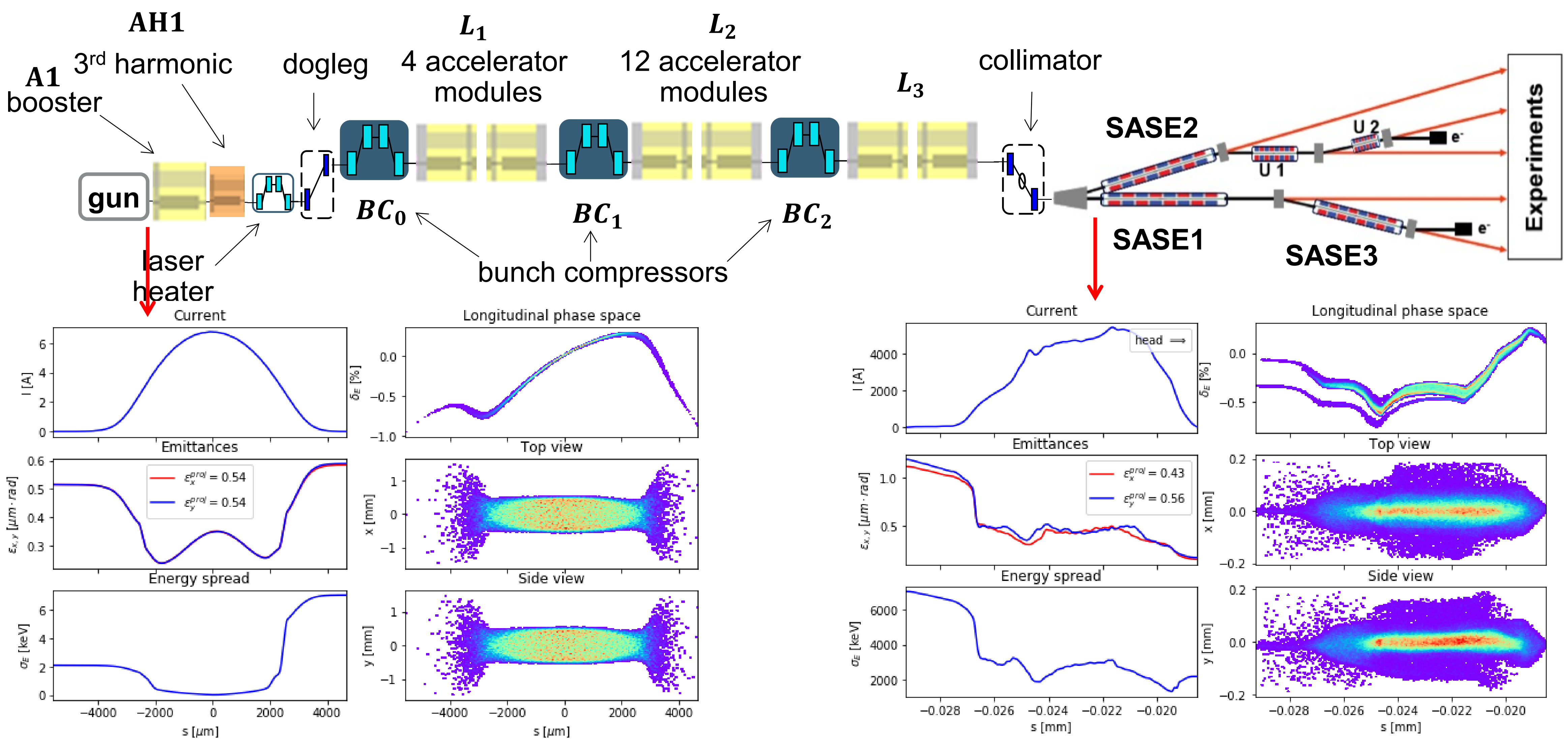
- A set of longitudinal beam dynamics parameters & a set of RF parameters aiming for ~5 kA at 100 pC, e.g.

Energy, MeV	110	500	2000
R56, mm	73.8	76.4	24.1
Compression	3	30	830
With Z_3', 1/m = 0 & Z_3'', 1/m/m = 1000			

RF	V_{A1}, MV	φ_{A1}, deg	V_{AH1}, MV	φ_{AH1}, deg	V_{L1}, MV	φ_{L1}, deg	V_{L2}, MV	φ_{L2}, deg
	124.12	-8.899	22.68	138.807	414.85	19.93	1799	33.5

- **Note, the power of the laser heater model chosen to produce an energy modulation amplitude on axis & to have after compression an rms slice energy spread near to e.g. 2-3 MeV based on micro bunching studies**

A fast estimation for S2E BD in OCELOT (cont'd)

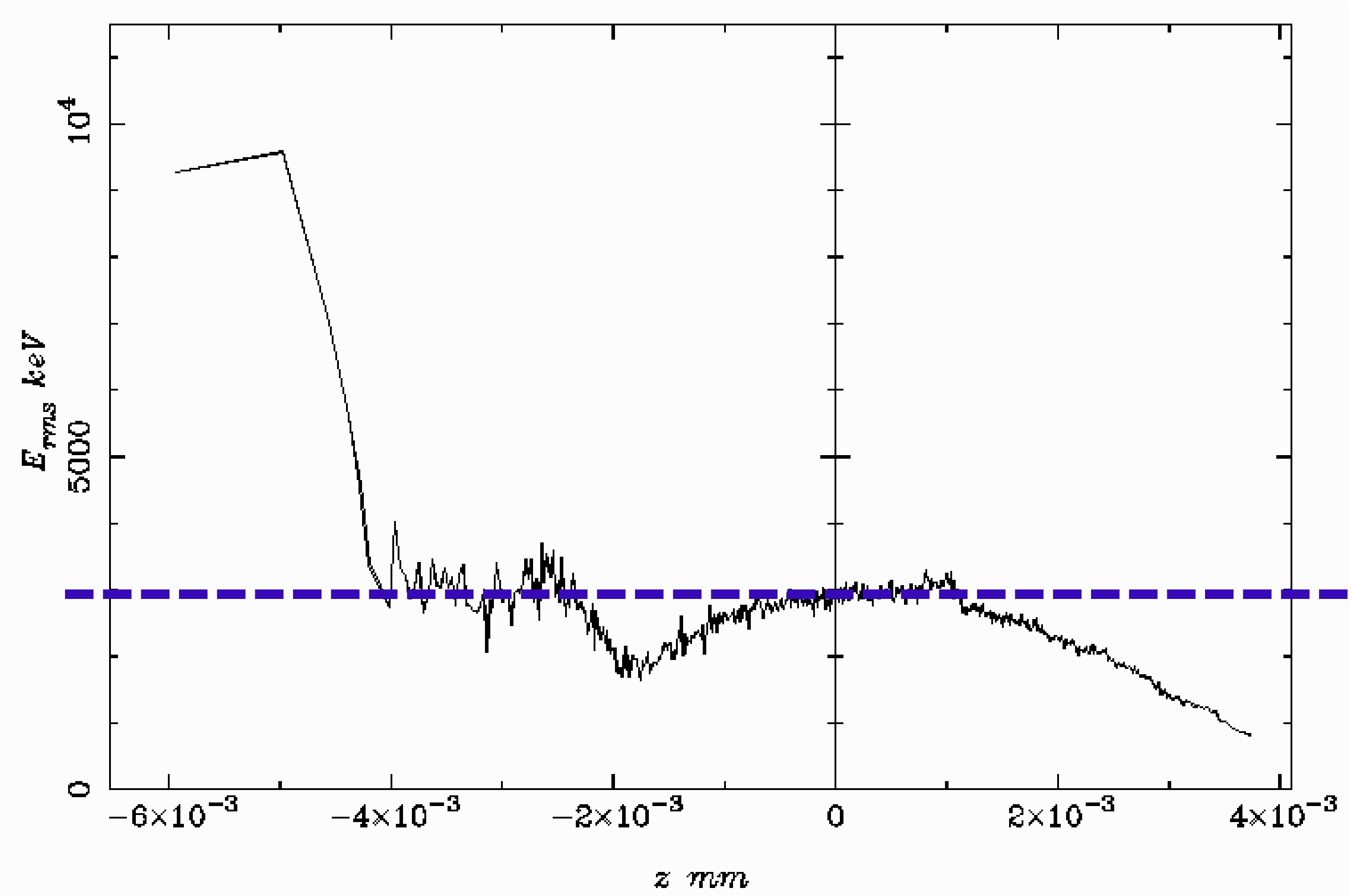


NO micro bunching effect possibly considered in these simulations

A fast estimation for S2E BD in OCELOT (cont'd)

Bunch Qualities before Undulators

Slice energy spread

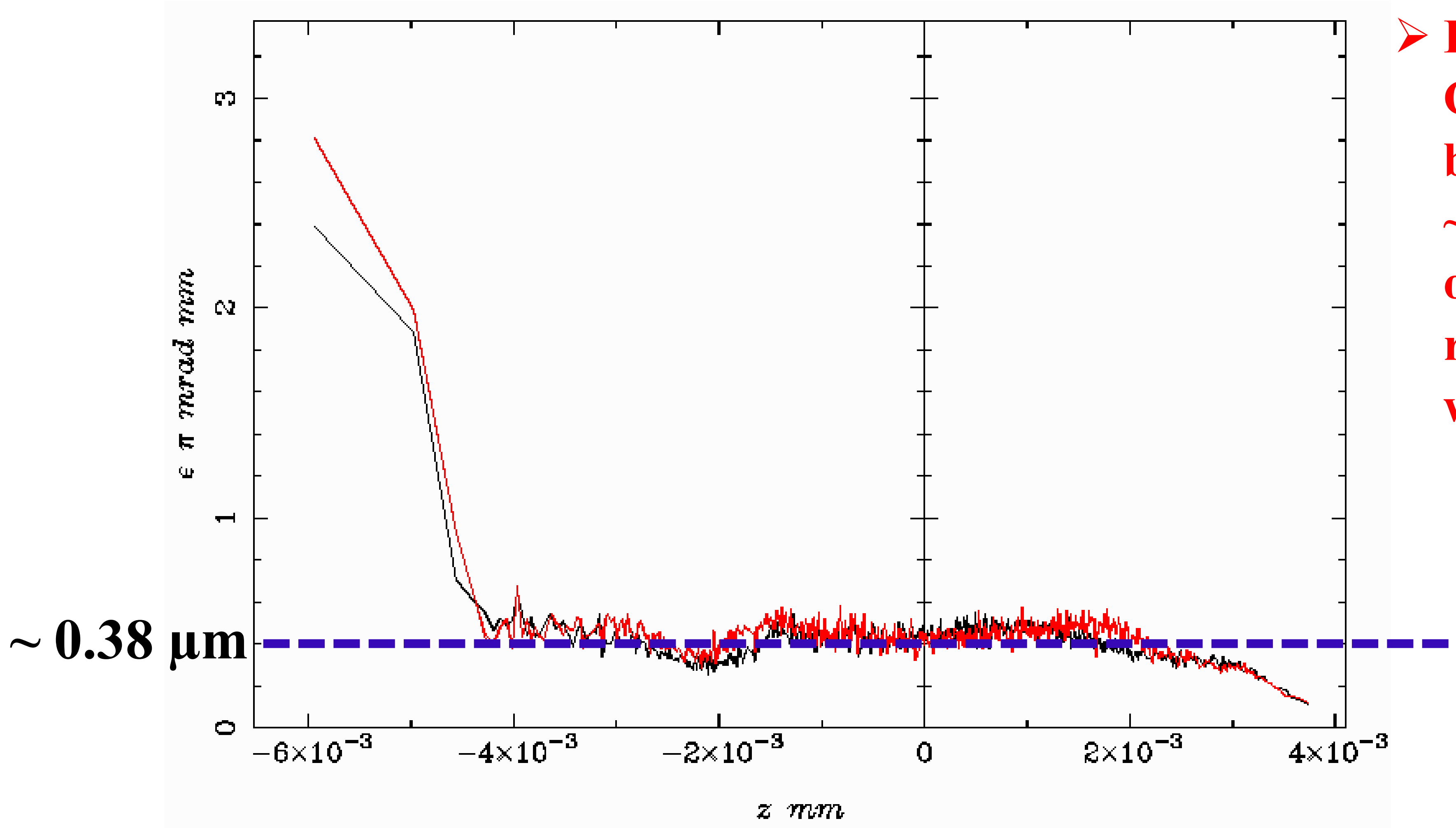


~ 3 MeV

A fast estimation for S2E BD in OCELOT (cont'd)

Bunch Qualities before Undulators

Slice emittance



- **First estimations by OCELOT show the emittance before undulators can be ~conserved compared to that of the injector bunch for a reasonably high peak current when all collective effects on**

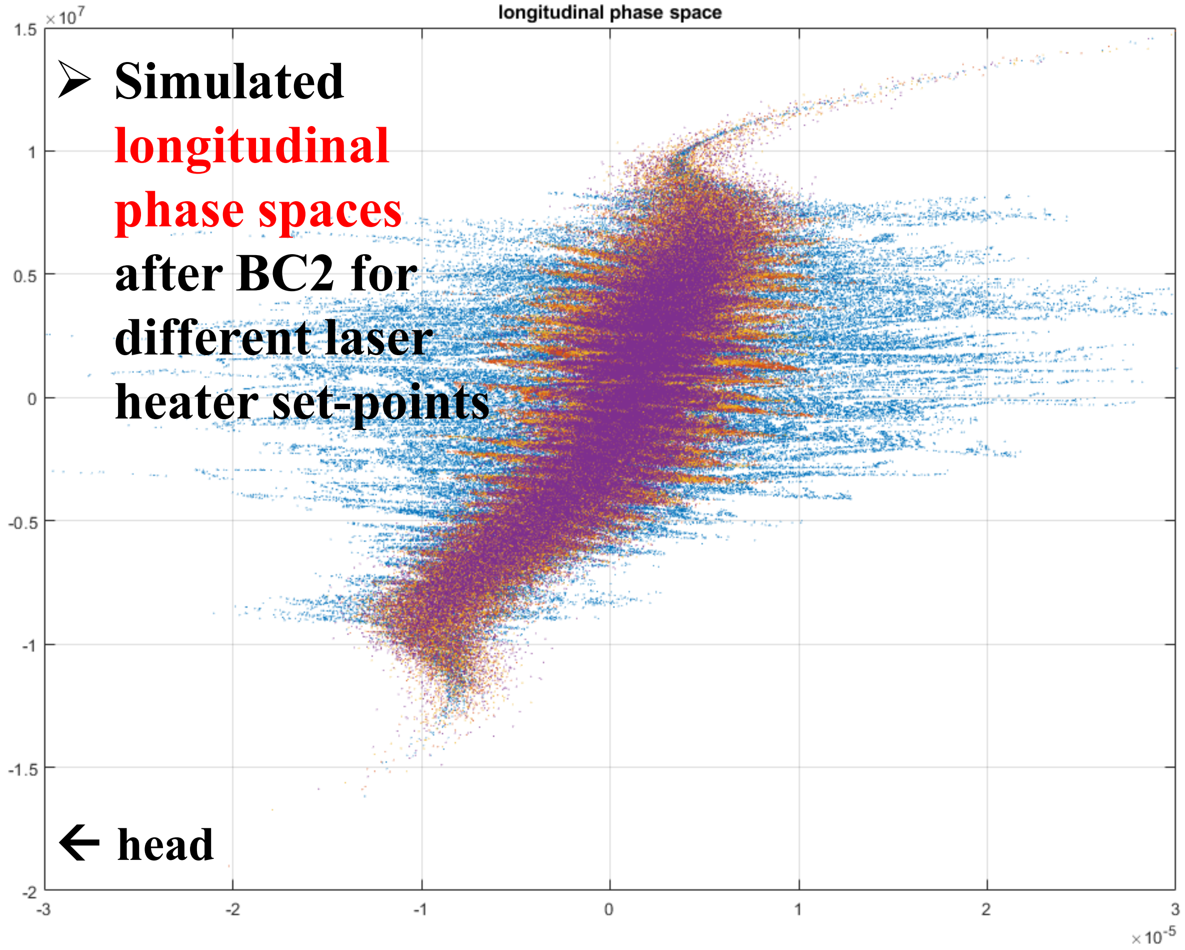
Beam dynamics with Impact-Z (M. Dohlus)

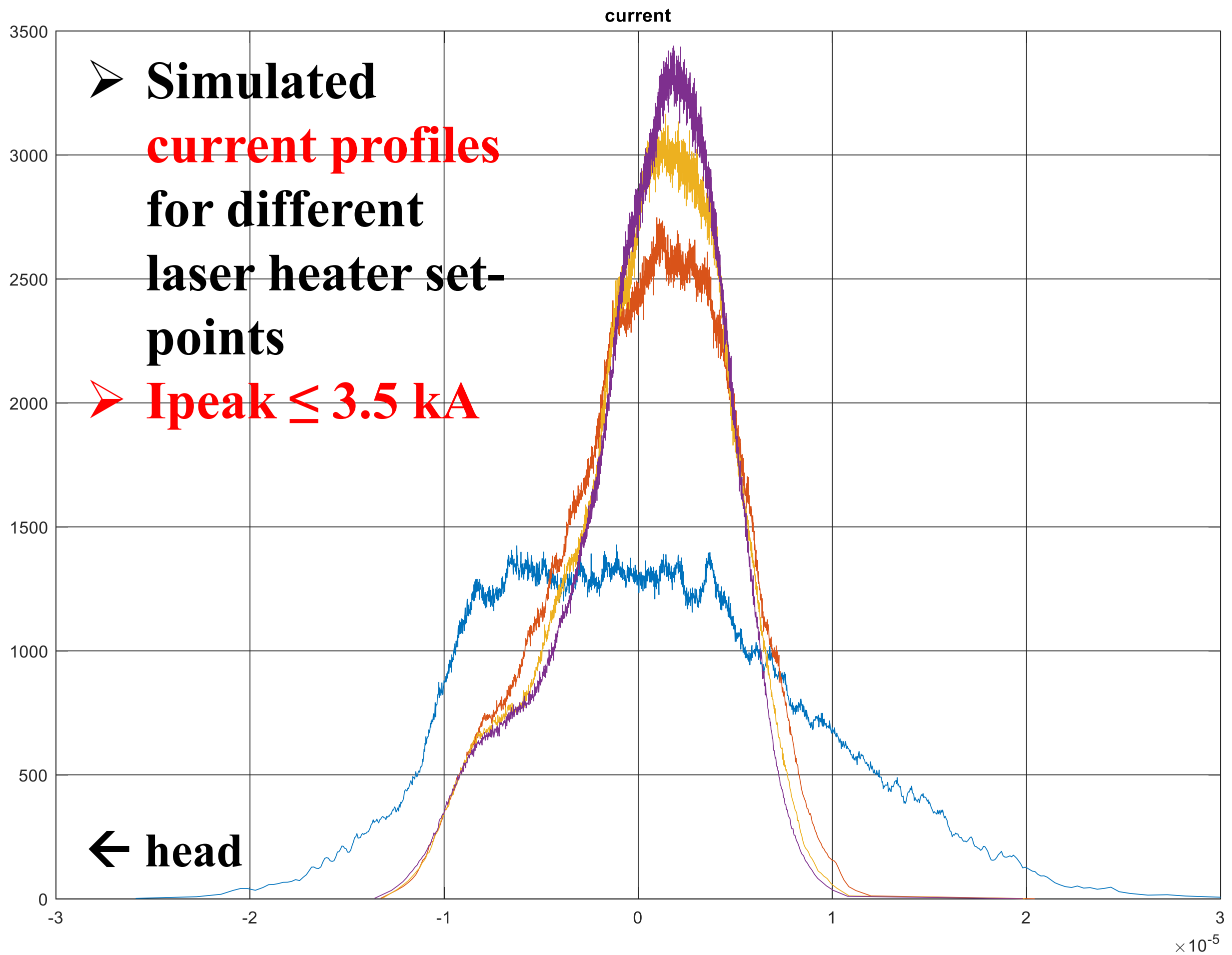
→ Microbunching effect

→ **ongoing** investigations with huge number of simulation particles & very fine numerical resolution

Fine Simulations with Impact-Z using 62 Millions macro particles for 100 pC (1 simulation particle ~ 10 electrons) → ongoing simulations

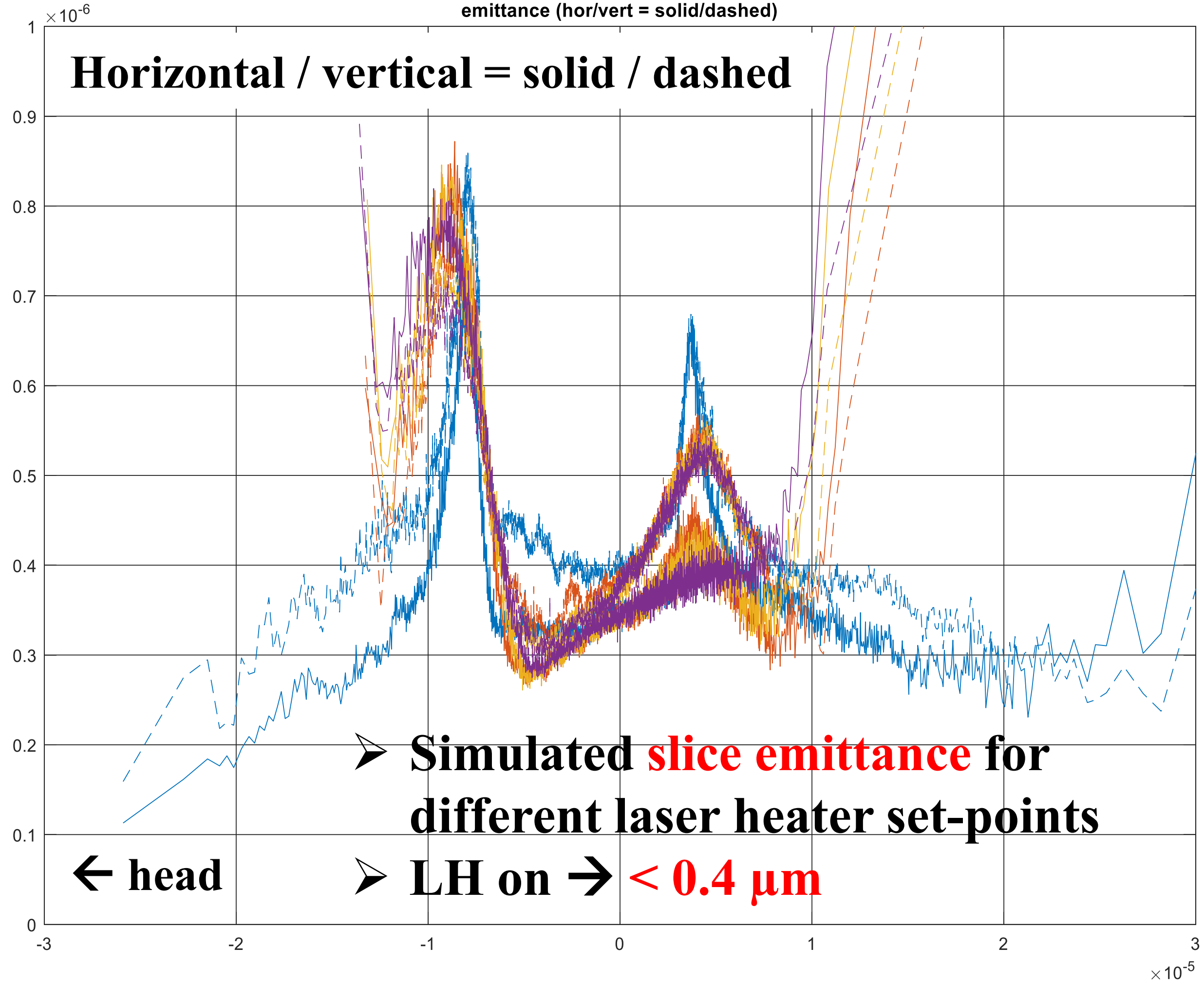
Laser Heater (LH) set-point: 0 eV/3300 eV/4000 eV/5000 eV



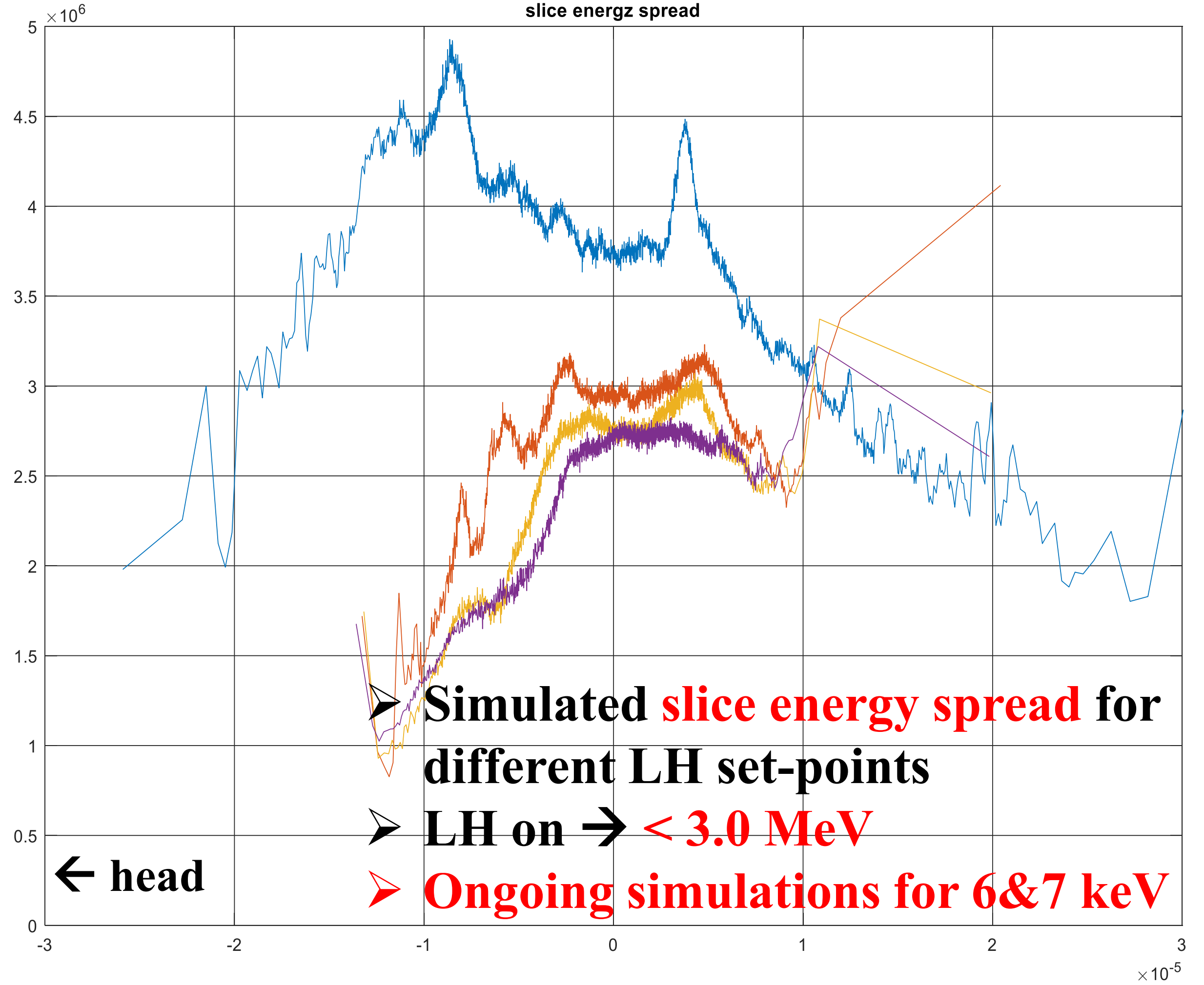


Fine Simulations with Impact-Z using 62 Millions macro particles (cont'd)

LH set-point: 0 eV/3300 eV/4000 eV/5000 eV



- Simulated **slice emittance** for different laser heater set-points
- LH on → **< 0.4 μm**



- Simulated **slice energy spread** for different LH set-points
- LH on → **< 3.0 MeV**
- **Ongoing simulations for 6&7 keV**

Summary & Outlook

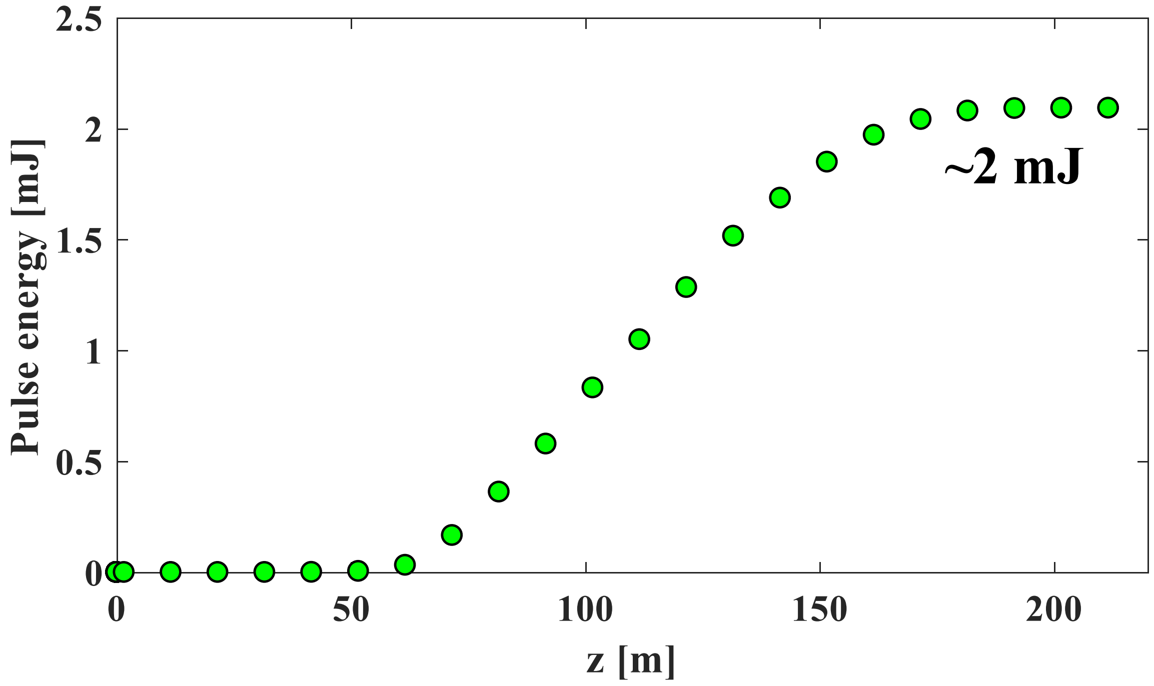
- **No final numbers yet**
- **S2E BD** with one of the optimized bunches from a SRF CW injector
  - → First results indicating bunch **emittance can be ~conserved** till undulator entrance while being **compressed to ~kAs**
    - → Estimated by OCELOT w/o micro bunching & being simulated by Impact-Z with micro bunching (ongoing)
    - → Warm-up lasing studies indicating **SASE signals** of mJ & hundreds μJ @ 0.24 & 0.17 nm w/o tapering / beta optimization / undulator modification
- Continuing work towards CW regime
  - → **Injector** optimization
  - → **Compression** scenarios
  - → **Tool** studies for covering all collective effects properly
  - → Systematic **SASE** studies
  - → **Undulator** R&D, etc.

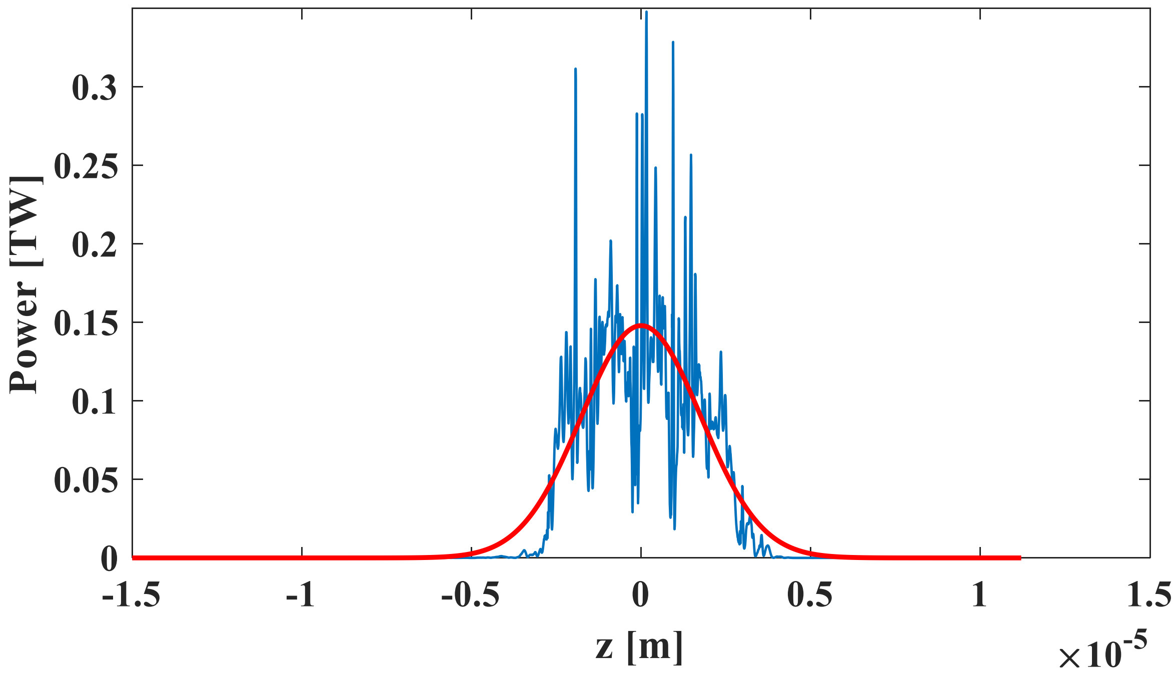
Backup Slides: SASE Simulations

Lasing @ 0.24 nm with the impact-Z bunch ("µB on") at a laser heater set-point of 5 keV

→ 100pC, ~8GeV, ~3.2kA, SA1

→ w/o any optimization or modification to undulator configuration





Lasing @ 0.17 nm with the impact-Z bunch ("µB on") at a laser heater set-point of 5 keV

→ 100pC, ~8GeV, ~3.2kA, SA1

→ w/o any optimization or modification to undulator configuration