PART II

Beam dynamics from injector exit to undulator for a conceptional CW XFEL

Ye Chen and Martin Dohlus
Hamburg, 16.12.2020

Thanks to involved colleagues from MPY, MXL, PITZ, MSL, MSK…
Acknowledgements to Dr. J. Qiang from LBNL for Impact-Z/T code support.

Cornerstones

CW Proposal

NIM A 768 20-25 (2014)

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

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.

Cornerstones (cont'd)

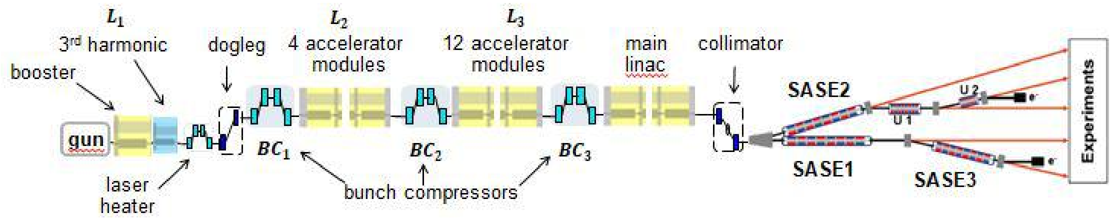
Gun Choice

DESY Injector Strategy Meeting 2020

Choice of the gun for CW operation of the European XFEL

Igor Zagorodnov and Martin Dohlus
DESY, Hamburg

March 10, 2020



first studies w/o full optimization

Before SASE1

parameter	Pulsed mode		CW mode (100 pC)		
	250 pC	100 pC	SC gun	NC gun	Cold gun
Projected x-emittance, μm	**0.63**	0.29	0.67	0.33	0.37
Projected y-emittance, μm	**1.08**	0.74	1.45	1.10	1.02
Slice x-emittance, μm	**0.50**	0.23	0.75	0.35	0.23
Slice y-emittance, μm	**0.55**	0.28	0.80	0.50	0.35

European XFEL

Recent Work

R&D Status Summary

XFEL R&D Report 2020

Elmar Vogel for all colleagues working on a future CW operation mode of the European XFEL
@ all virtual XFEL R&D Report Days 2020, December 1st 2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

MATTER AND TECHNOLOGIES

DESY.

Summary and Outlook

towards CW operation of the superconducting XFEL accelerator

CW upgrade of the European XFEL

- operation with pulsed rf or with cw rf at lower energy but with flexible time structure

Main Linac / Linac III

- moving present linac I and linac II modules to the end
- the RF for four modules is provided by one klystron in pulsed operation and two IOTs in CW operation
- RF control is under development, MIMO comes next
- resent CW module test: beam energy after linac III depends on cooling capability

Linac I and Linac II

- require CW optimized modules, couplers and cavities, combining high Q (for CW RF) and high gradients (for pulsed RF)
- Cavities treated by Nitrogen Infusion and Large Grain Cavities are being studied

Injector

- CW L-band SRF photo injector is the first choice, looks promising but requires still some development
- CW operation study of 3rd harmonic system started

Putting it all together – beam dynamics

- injector beam dynamics optimization studies just started, more to come
- injector-to-undulator (s2e) beam dynamics studies just started, first promising results, more to come

S2E beam dynamics

DESY. | Recent developments towards CW operation of the superconducting XFEL accelerator | Elmar Vogel @ all virtual XFEL R&D Report Days 2020, December 1st 2020 | Page 37

Stage Goals till Dec.2020

+ Codes used so far

- SRF-gun based CW injector optimization
  ASTRA + Optimizer from LBNL

- Start-to-End beam dynamics till undulator entrance
  OCELOT

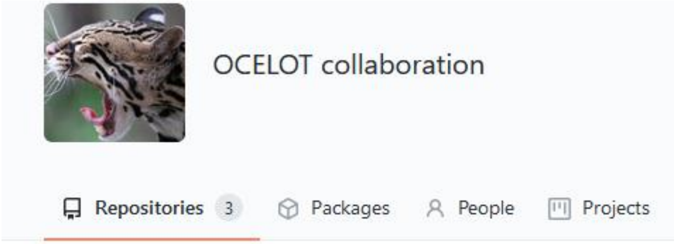
  → **Justifying bunch qualities obtained from injector optimization**
  → **Preparing for full S2E optimization downstream injector**

- Dedicated numerical studies with high resolution
  IMPACT-Z

  → **Considering e.g. micro bunching effects**

ASTRA

https://www.desy.de/~mpyflo/



https://github.com/ocelot-collab

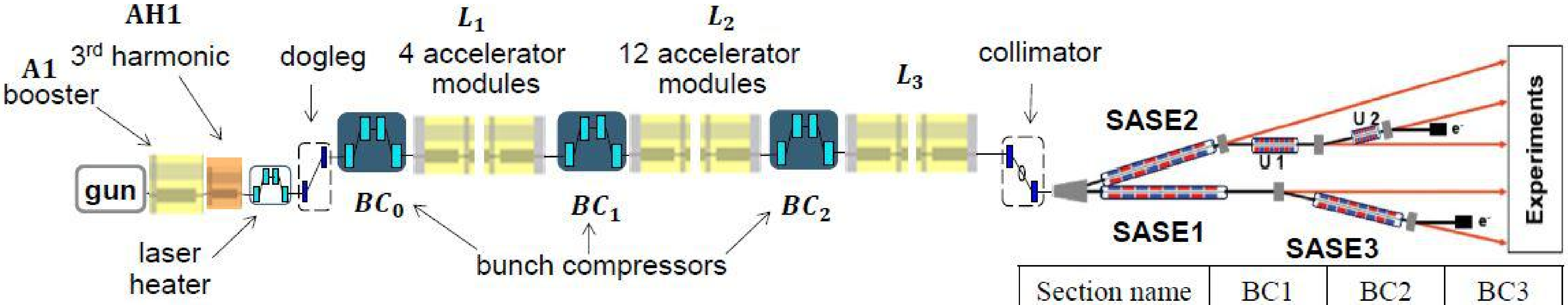
BERKELEY LAB
Bringing Science Solutions to the World

IMPACT: Integrated Map and Particle ACcelerator Tracking Code

https://amac.lbl.gov/~jiqiang/

The XFEL

Machine Layout



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

Nature Photonics 14, 391–397(2020)

nature > nature photonics > articles > article

Article | Published: 18 May 2020

A MHz-repetition-rate hard X-ray free-electron laser driven by a superconducting linear accelerator

W. Decking, S. Abeghyan, [...] D. Zybin

Nature Photonics **14**, 391–397(2020) | Cite this article

- For simplicity, downstream CW injector, overall machine layout stays similar for now
- Working points (w.r.t. rf parameters) & BD parameters varied for first S2E case studies in CW regime

Energy Gain Budget in CW Regime

Inputs from Elmar Vogel, MSL

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

- **Preliminary energy profile for S2E simulations**

→110 / 500 / 2000 / 8000 MeV for
BC0 / BC1 / BC2 / final energy

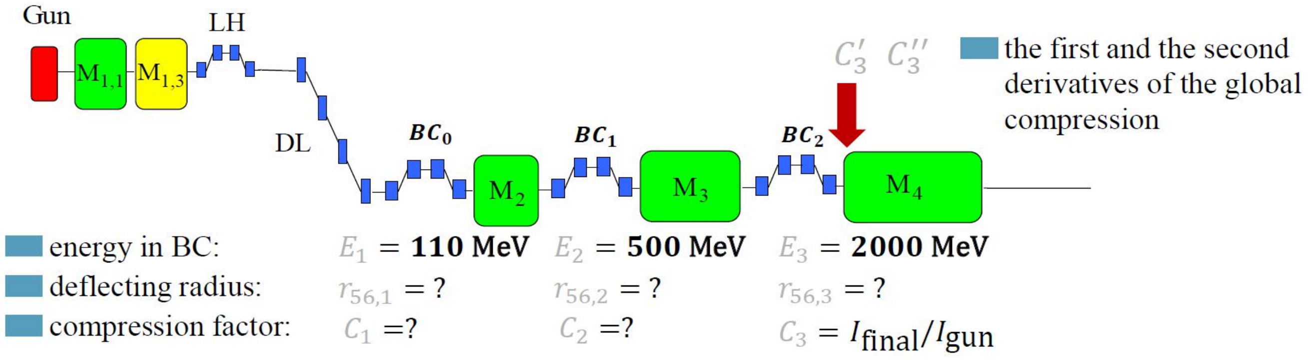
[1] LCLS-II Final Design Report DRAFT, December 21, 2014

[2] Kickoff BD meeting for CW Project, 10.2020

Start-to-End Simulation Capability

In a Nutshell

- **Multi-parametric optimization** considering rf tolerance & collective effects
  - → Searching for an optimal choice of parameters e.g. E1/E2/E3→C3→C3′→r1→C1/C2/r2/r3→C3″
  - → Final bunch length & peak current sensitive to energy chirp, thus to rf parameters
  - → Mapping rf parameters to longitudinal beam dynamics parameters[1,2]
- **Collective effects**
  - → 3D SPACE CHARGE / 3D WAKE / 1D CSR (arb. trajectories)
  - → Tools used
    - → **Injector[3,4]:** ASTRA or KRACK3
    - → **Injector to Undulator:** OCELOT, IMPACT-Z
    - → **Undulator:** GENESIS / OCELOT-ADAPTER



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

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

→ **implementation in ocelot**

Mapping rf to LBD parameters with ocelot:

[1] I. Zagorodnov et al., Phys. Rev. Accel. Beams 22 024401 (2019)

[2] S. Tomin et al., IPAC2017, WEPAB031

Detailed injector BD:

[3] Y. Chen et al., Phys. Rev. Accel. Beams 23, 044201 (2020)

[4] I. Zagorodnov et al., arXiv:2010.10204

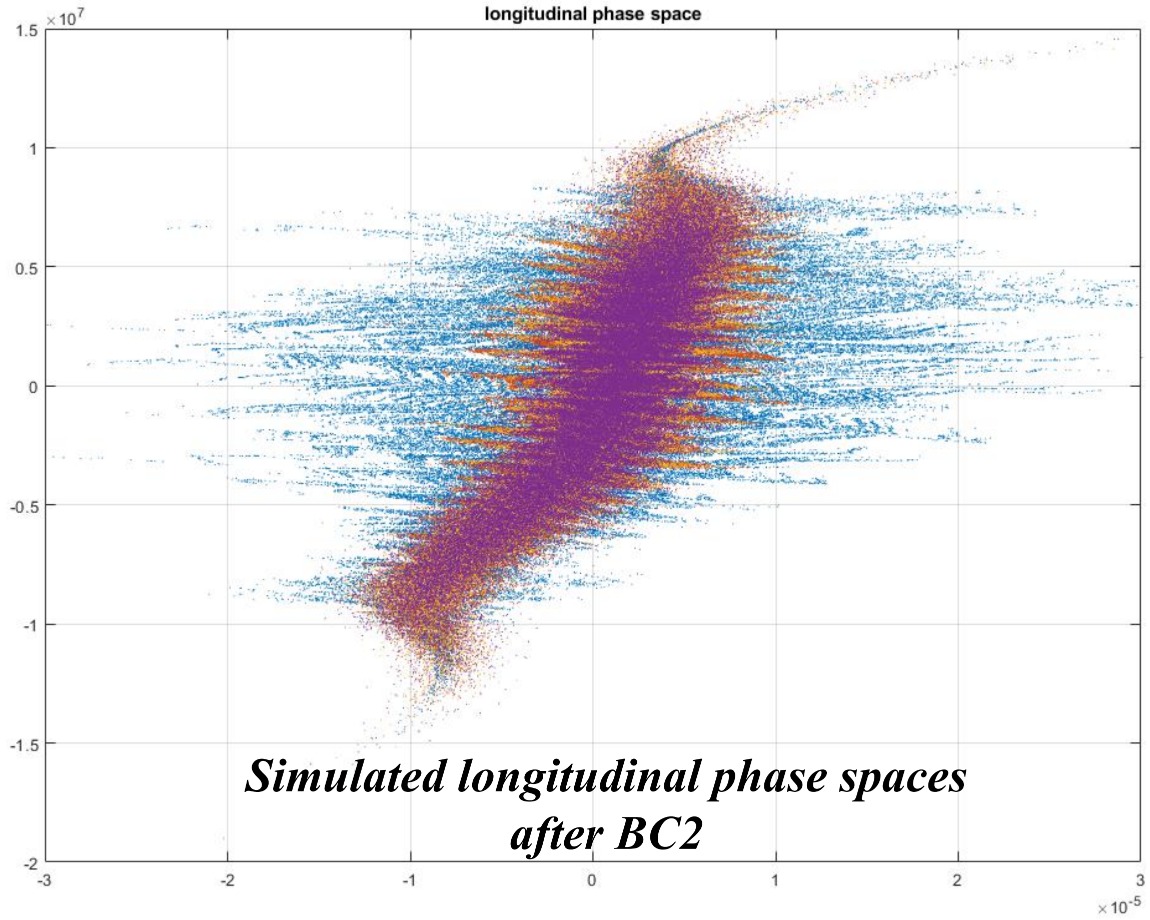
Study I:

Particle tracking with high numerical resolution for micro bunching studies

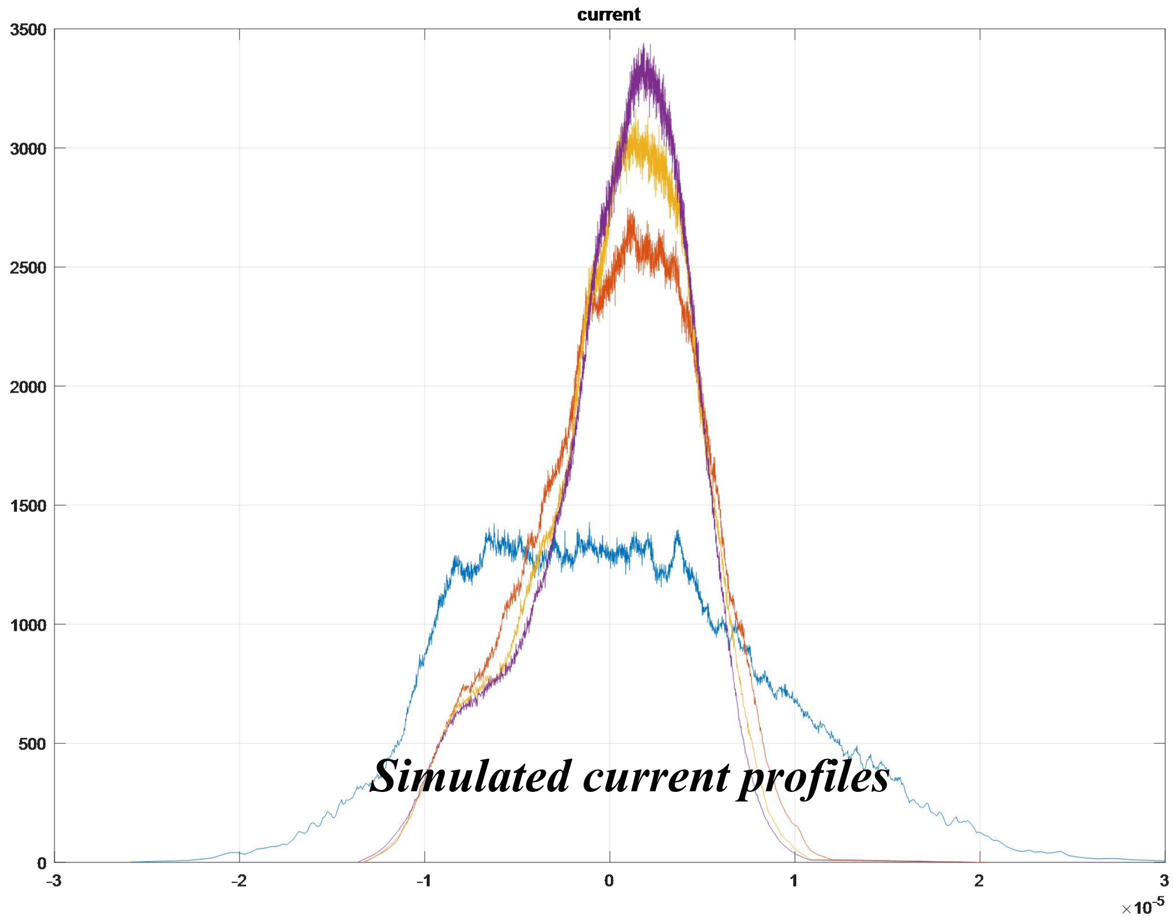
Bunch Quality Studies vs. Laser Heater Set-Points

62,000,000 macro-particles used for 100 pC → 1 simulation particle ~ 10 electrons

Laser Heater Set-Points: 0 eV/3300 eV/4000 eV/5000 eV



Simulated longitudinal phase spaces after BC2

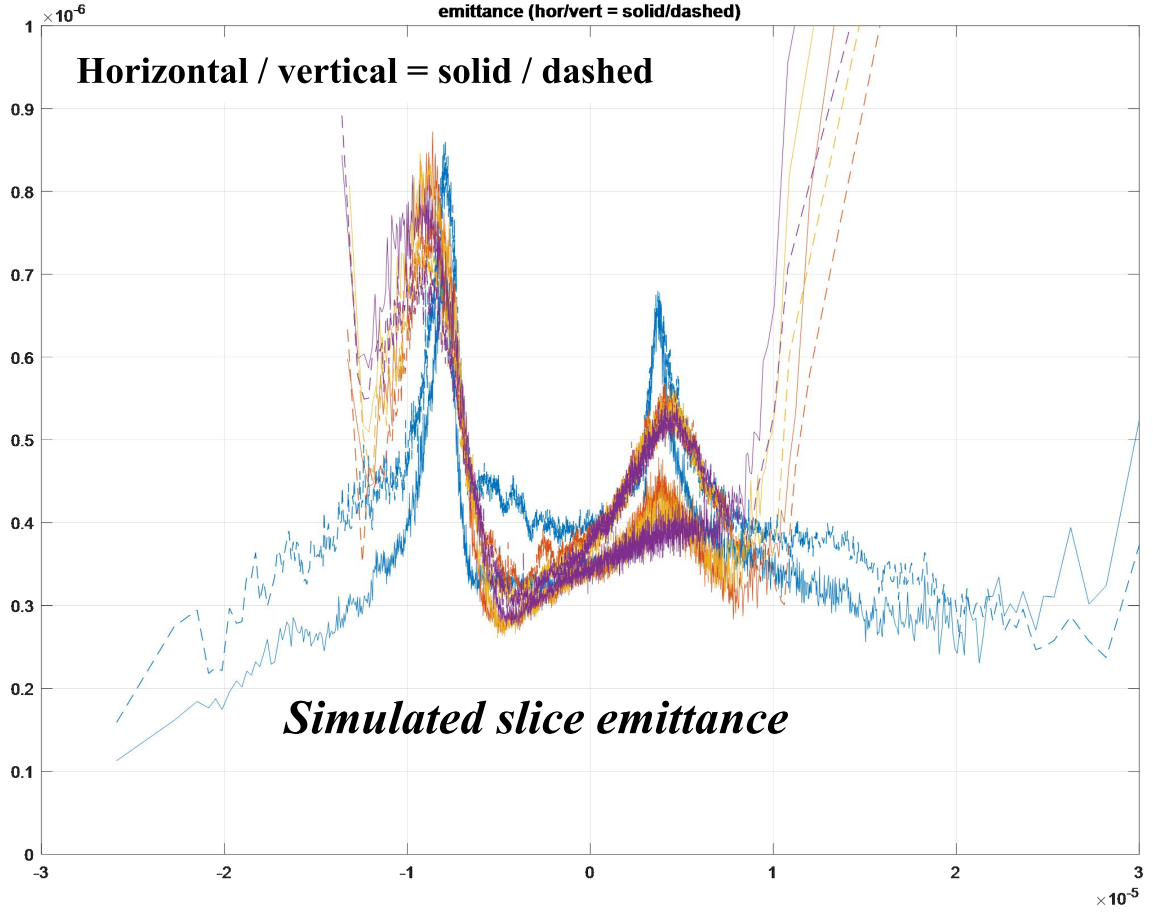


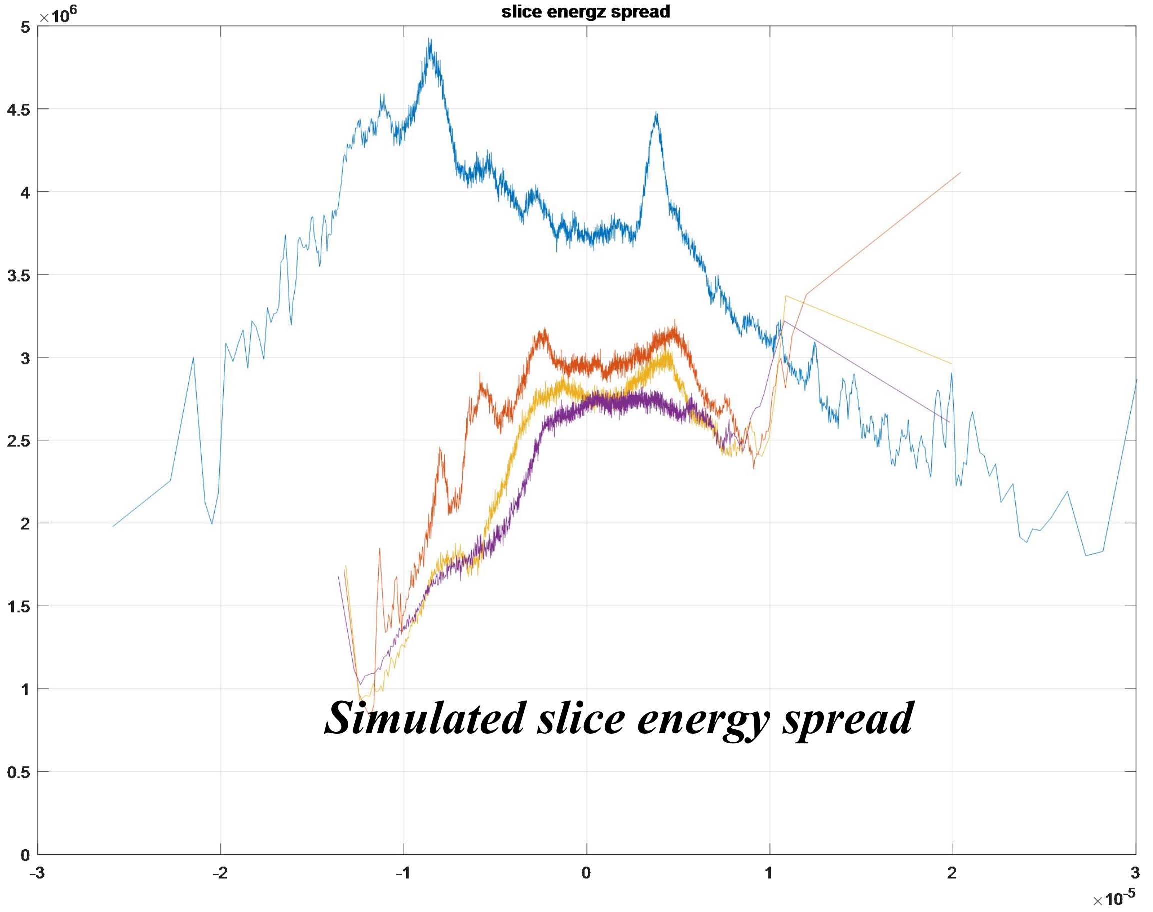
Simulated current profiles

Bunch Quality Studies vs. Laser Heater Set-Points

62,000,000 macro-particles used for 100 pC → 1 simulation particle ~ 10 electrons

Laser Heater Set-Points: 0 eV/3300 eV/4000 eV/5000 eV

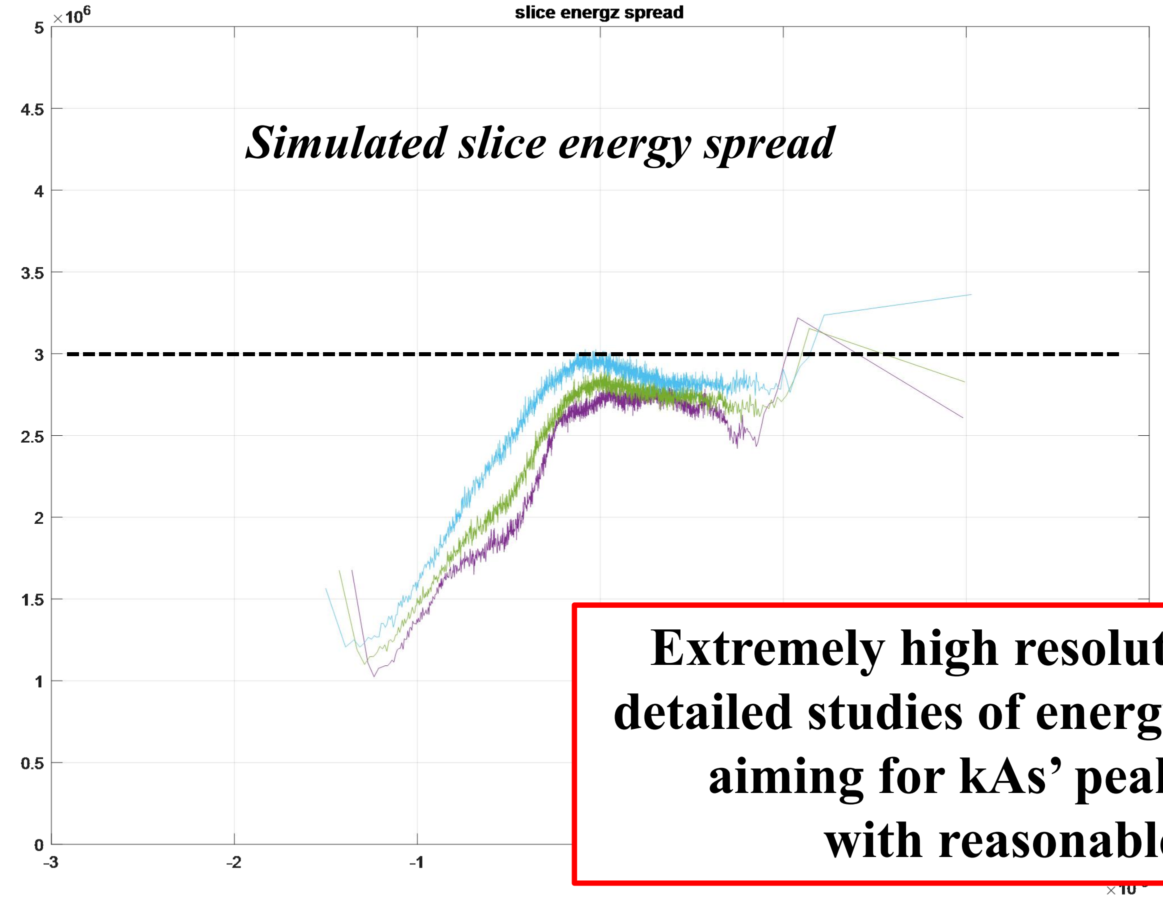


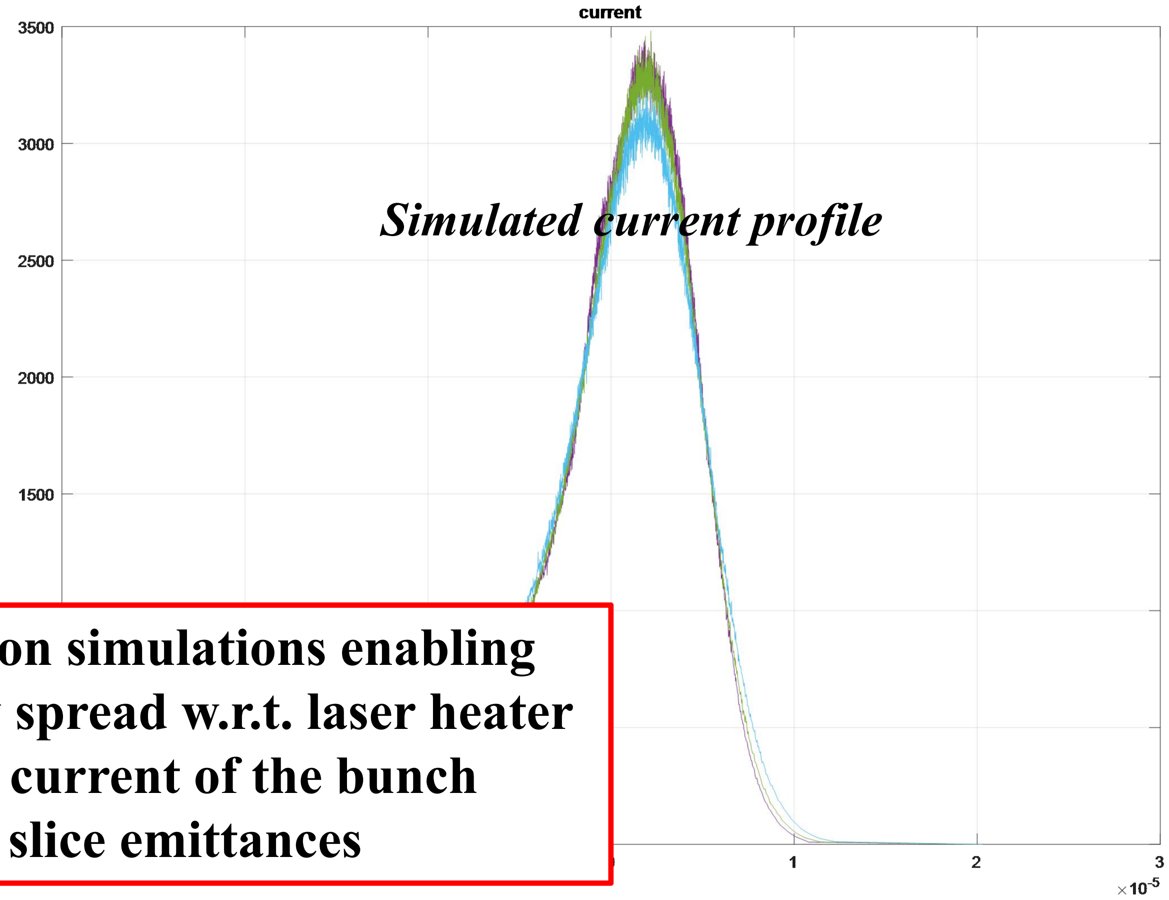


Bunch Quality Studies vs. Laser Heater Set-Points

62,000,000 macro-particles used for 100 pC → 1 simulation particle ~ 10 electrons

LH SP: 5keV / 6keV / 7keV





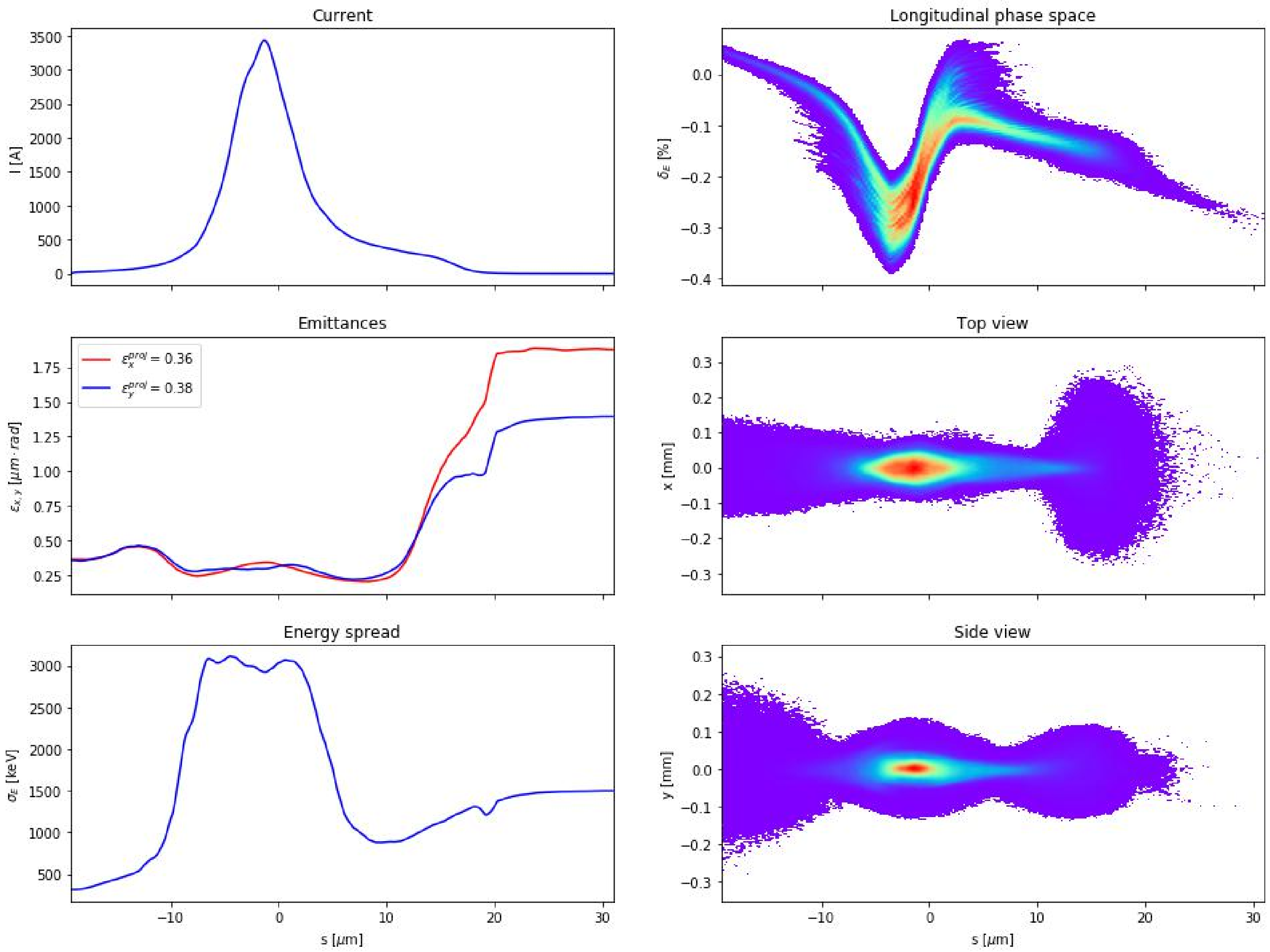
Extremely high resolution simulations enabling detailed studies of energy spread w.r.t. laser heater aiming for kAs' peak current of the bunch with reasonable slice emittances

Study II:

Particle tracking in Ocelot for injector-case-studies (cases A/B/C obtained from CW injector optimization)

Tracking the Bunch till Undulator Entrance

"Injector Case A"

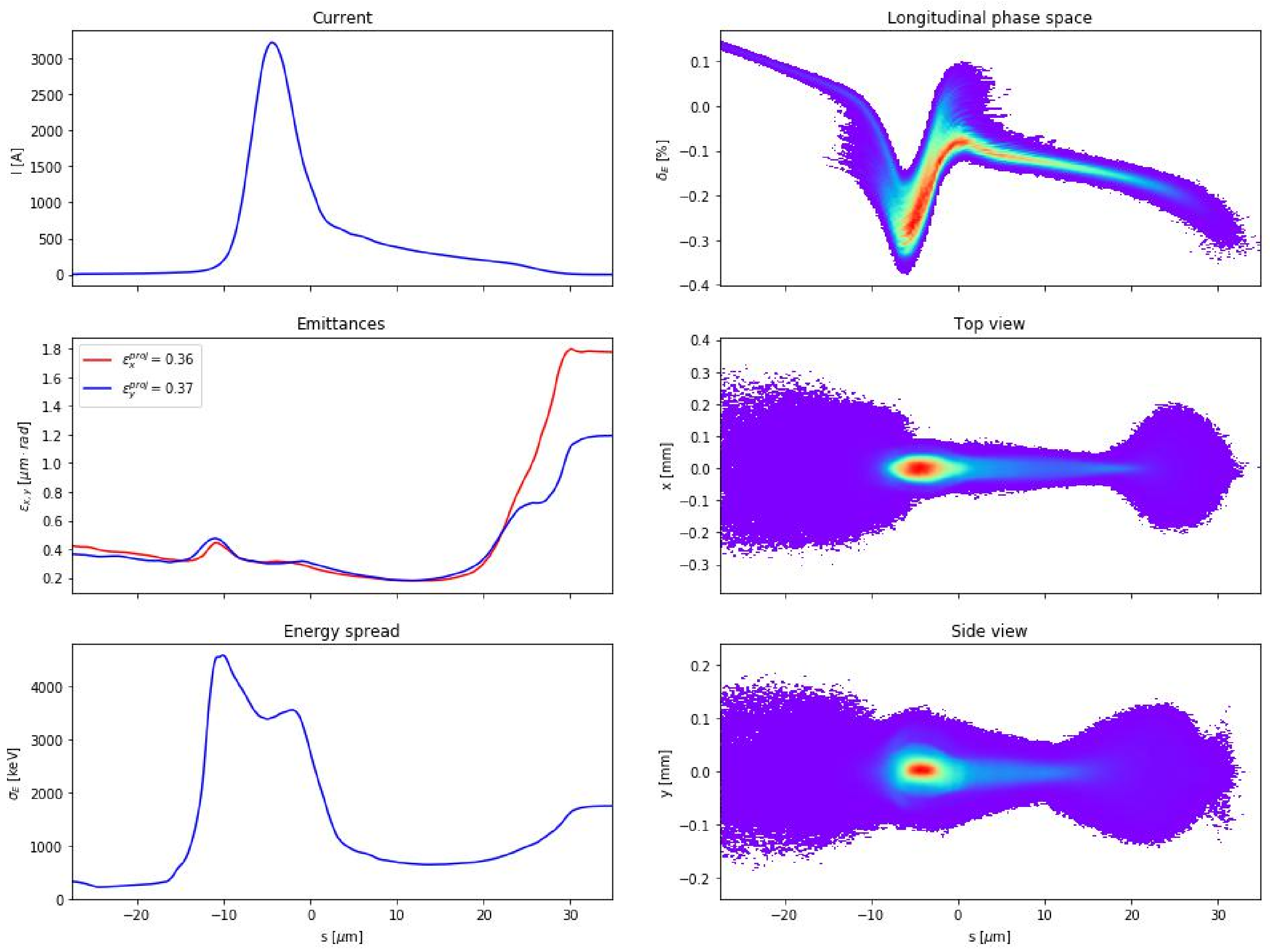


Case Study A

- Current peak ~ 3.4 kA
- Slice emittance ~ 0.33 μm
- Slice energy spread ~ 3 MeV

Tracking the Bunch till Undulator Entrance

"Injector Case B"

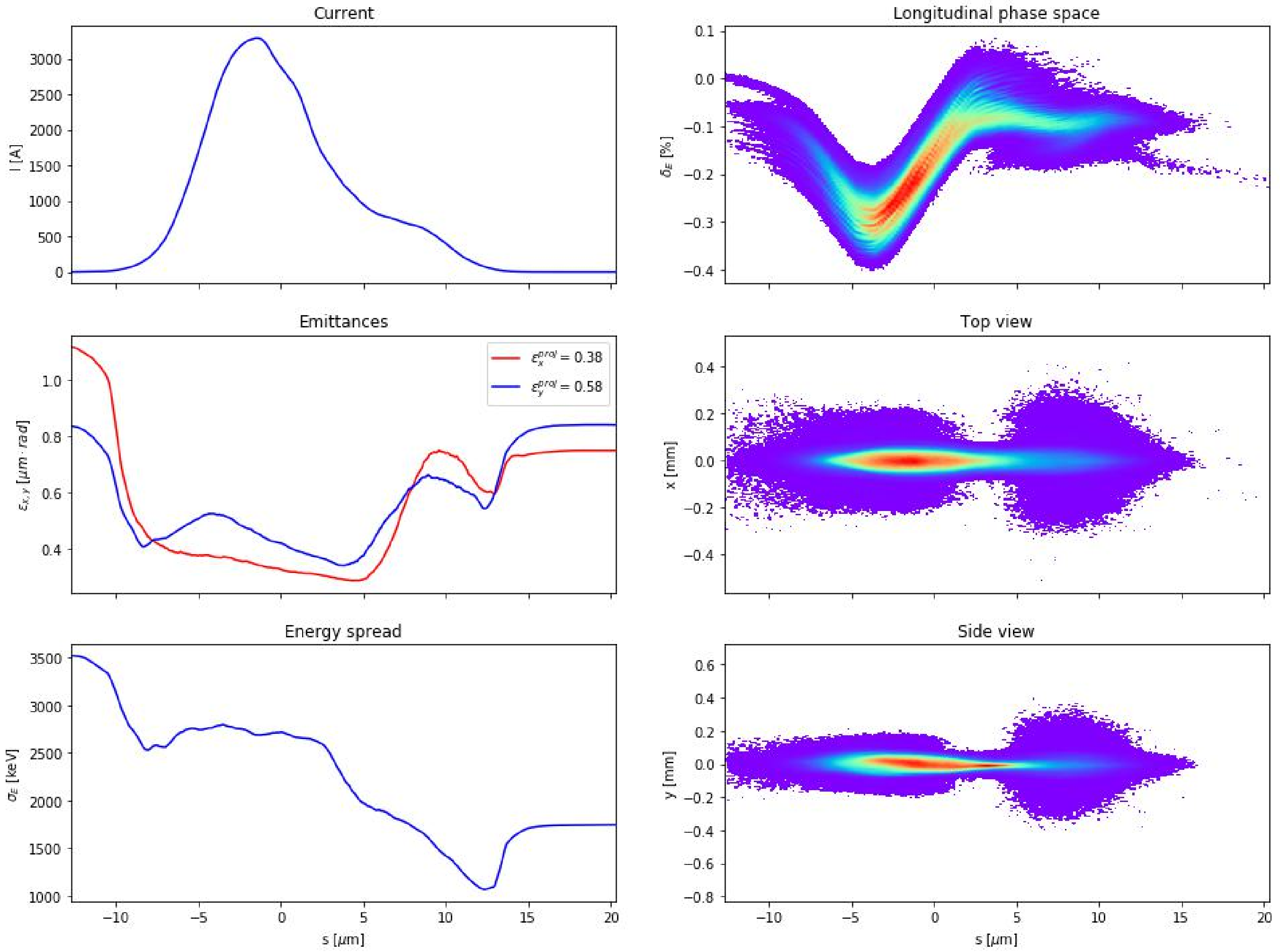


Case Study B

- Current peak ~ 3.25 kA
- Slice emittance ~ 0.3 µm
- Slice energy spread ~ 3.4 MeV

Tracking the Bunch till Undulator Entrance

"Injector Case C"



Case Study C

- Current peak ~ 3.33 kA
- Slice emittance ~ 0.40 μm
- Slice energy spread ~ 2.7 MeV

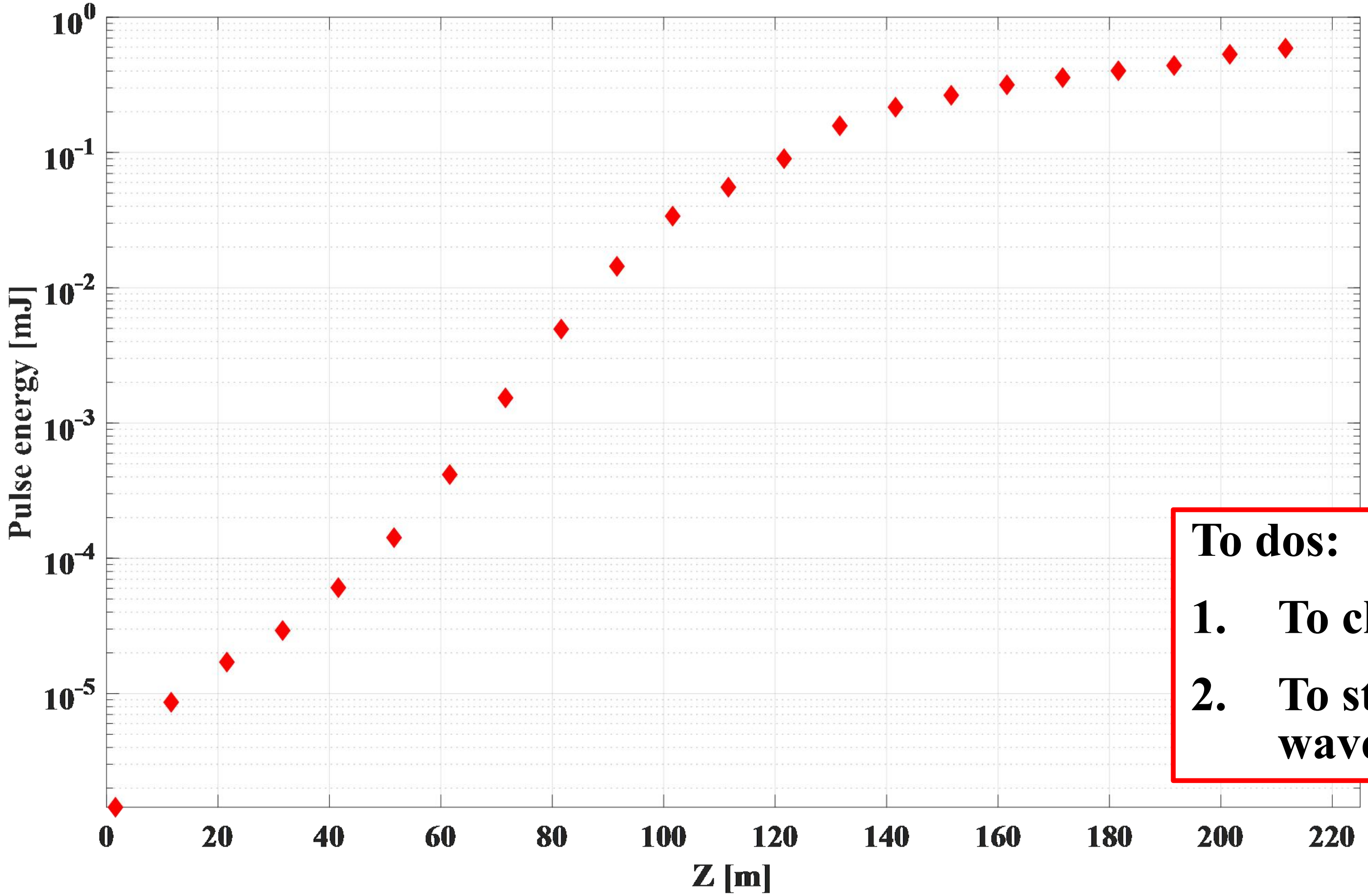
1. **Injector emittance optimization not final yet**
2. **Results must be strictly checked with higher numerical resolution (to be done)**
3. **First 3 case studies in ocelot indicating these compressed bunches could be transported to undulator entrance without significant degradation**

Study III:

with presumably such bunch qualities, lasing possible?

Quick Glance at Lasing

first try



~0.6 mJ @ 9keV

To dos:

1. **To clarify the wavelength rage**
2. **To study/optimize SASE at a few wavelengths of interest**

Summary

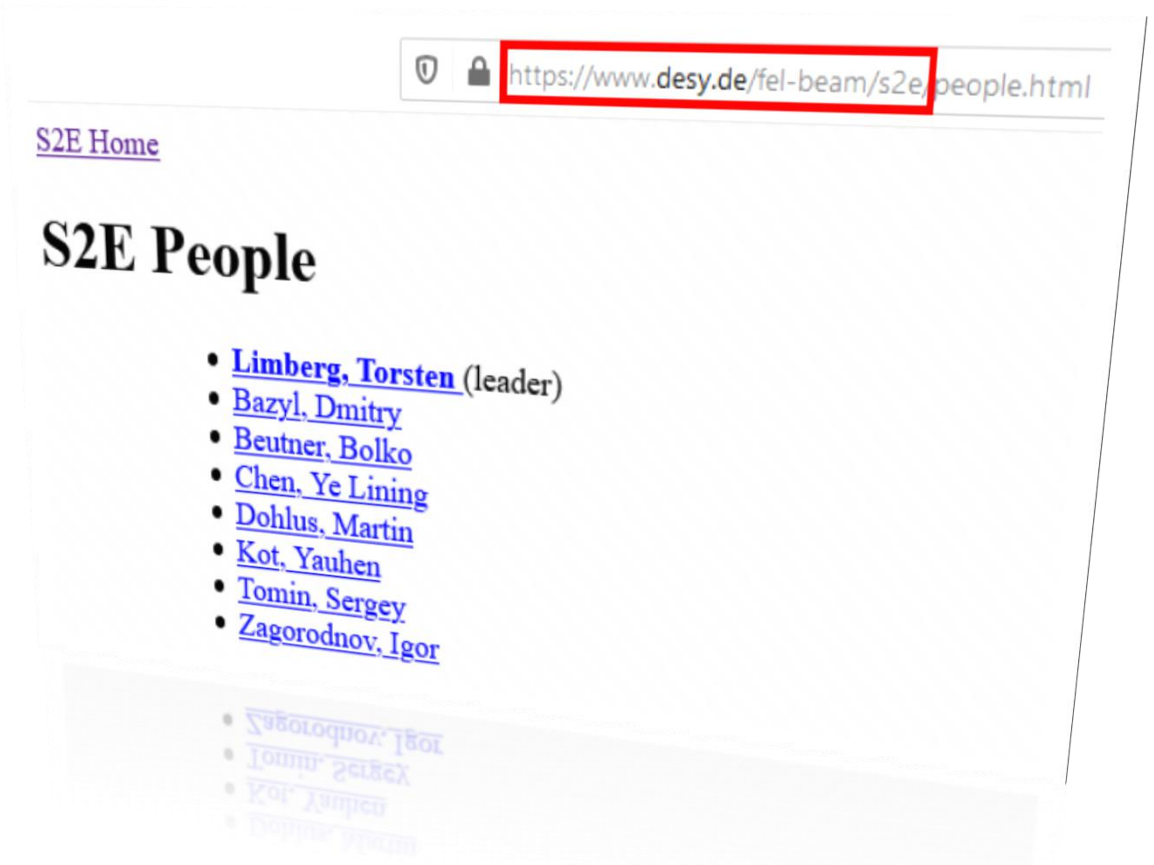
Status 16. Dec. 2020

- **Start-to-End beam dynamics studies in the CW regime started**
- **First S2E simulations carried out** using optimized electron bunches from the optimization of a SRF-gun based CW injector
  - → **Capability studies** with Impact-Z & Ocelot
  - → **Case studies** showing **promising** results of the bunch qualities obtained in front of the undulators (to be checked)
- Very **challenging** task with high-resolution simulations when using huge number of macro-particles (numerical issues to be tackled)

Thank You

Thanks to involved colleagues from MPY, MXL, PITZ, MSL, MSK, MCS…

Acknowledgements to Dr. J. Qiang from LBNL for Impact-Z/T code support.



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