Start-to-End (S2E) Simulations for the XFEL

J.P. Carneiro, W. Decking, M. Dohlus, B. Faatz, N. Golubeva, K. Flöttmann, Y. Kim, T. Limberg, E. Saldin, E. Schneidmiller, F. Stulle, M. Yurkov
In collaboration with: P. Emma (SLAC) and P. Piot (FNAL)

Introduction:

X-ray FELs will be the first accelerator projects with key performance depending exponentially on beam quality:

$$P_{rad} = P_0 \exp(z/L_G)$$

$$L_G = \frac{1}{\sqrt{3}}\left(\frac{I_A \gamma^3 \sigma_r^2 \lambda_u}{4\pi \hat{I} K^2}\right)^{1/3}$$

L_G: Power gain length
$\hat{I}$: Peak Current
σ_r: Transverse beam size

Thus, the reliable understanding of beam dynamics is of paramount importance.

Start-to-End Simulations

Beam dynamics for the high intensity bunches of a SASE FEL driver linac is dominated by self-induced fields:

- Space Charge Fields
- Coherent Synchrotron Radiation Fields
- Wake Fields

As all these depend on details of the longitudinal bunch profile and there is no 'memory-erasing' device like a damping ring, we need to trace the bunch from cathode to undulator.

Simulation Tools:

Injector & space charge dominated sections:
ASTRA or PARMELA (cylindrically symmetric bunch; space charge computed using a cylindrical mesh). Point-like particles.
Bending systems (bunch compressors):
CSRtrack (Gaussian macro-particles for simulation of Coherent Synchrotron Radiation fields from first principles) or elegant (1-D model, pointlike particles).
Emittance-Dominated Transport:
elegant (takes into account geometric wakes (TESLA cavities) and resistive wakes). Point-like particles.
SASE-FEL:
GENESIS or FAST

Benchmarking Efforts:

Code Comparison for Simulations of Photo-Injectors
C. Limborg *SLAC,* Y.K. Batygin *SLAC* , J.-P. Carneiro, K. Floettmann *DESY* , L. Giannessi, M. Quattromini *Ente Nazionale per le Nuove Tecnologie l'Energia e l'Ambiente* , M. Boscolo, M. Ferrario, V. Fusco, C. Ronsivalle
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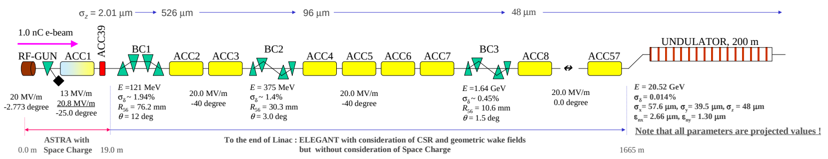
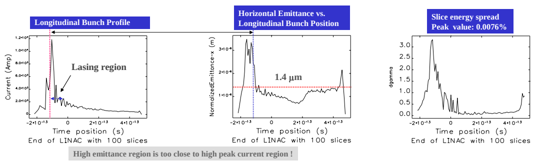
ICFA Mini-Workshop on CSR Calculation Benchmarking, Zeuthen 2002

ICFA Mini-Workshop on Benchmarking of Start-to-End Calculations, Zeuthen 2003

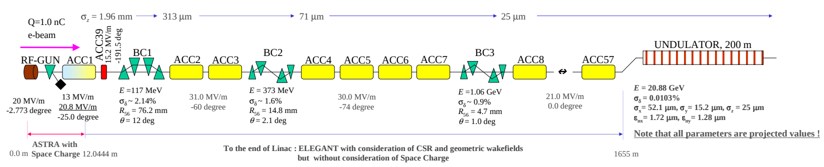
Results of TESLA XFEL S2E calculations

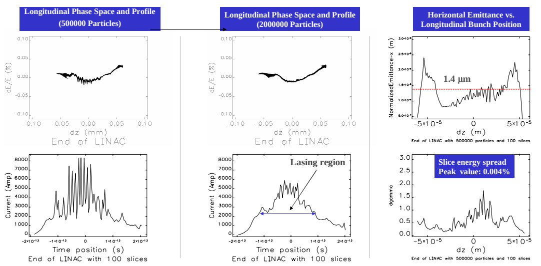
Required Beam Parameters for the XFEL project with 1.0 Å X-ray wavelength
Beam Energy ≥ 20.0 GeV **Transverse Slice Normalized RMS Emittance ≤ 1.4 µm**
Peak Current ≥ 5.0 kA **Slice Relative RMS Energy Spread ≤ 0.0125%**



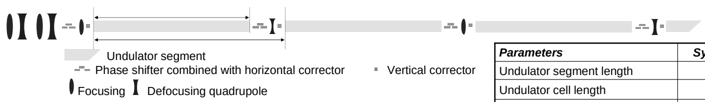


Different Compression Parameter Settings to Reduce Jitter Sensitivity



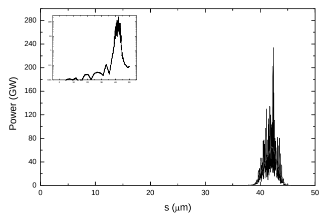


GENESIS Calculation Result (for peaked longitudinal distribution)



Undulator description for GENESIS calculations

Parameters	Symbol	Value	Unit
Undulator segment length	L_s	5	m
Undulator cell length	L_c	6.1	m
Undulator gap	g	10	mm
Undulator period (SASE1)	l_u	48	mm
Quadrupole optical length		192	mm
Quadrupole gradient at 20 GeV	Q	20	T/m

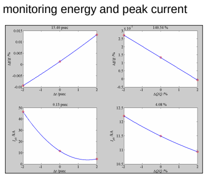


Radiated power along the bunch at saturation

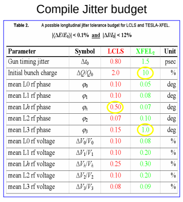
Topics for further investigation using S2E simulations:

Jitter:
'S2E' Study of Linac for *TESLA* XFEL , P. Emma

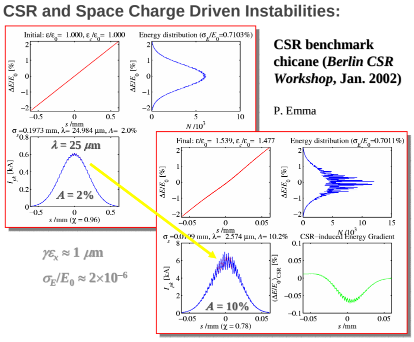
Scan gun-laser timing and charge, monitoring energy and peak current



Compile Jitter budget



CSR and Space Charge Driven Instabilities:

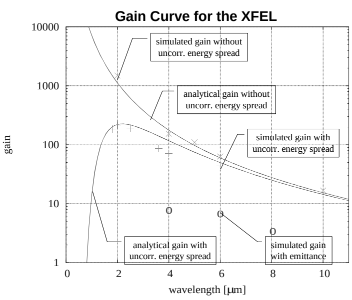


CSR benchmark chicane (*Berlin CSR Workshop*, Jan. 2002)

P. Emma

$\gamma\varepsilon_x \approx 1\ \mu m$

$\sigma_E/E_0 \approx 2\times10^{-6}$



Increase uncorrelated energy spread to cure instabilities:
Produce a FEL type modulation of the beam in the optical wavelength range by a laser pulse acting on the beam in an undulator. Afterwards the beam goes through a bunch compressor where these coherent energy modulations are quickly dissipated, leading to an effective "heating" of the beam. A similar mechanism takes place in storage ring FELs.

A numerical example for TTF2 (possibly for the XFEL):
The undulator with ten periods, a period length 3 cm, and a peak field 0.49 T is located in front of BC1. A fraction of power in the second harmonic (λ = 0.52µm) of the Nd:YLF laser system and is transported to the undulator. For a transverse size of the laser beam 0.5 mm (Rayleigh length is 1.5 m) and a power of 300 kW, the amplitude of energy modulation will be about 20 keV (rms energy spread is smaller by √2).

Responsible Author: Torsten.Limberg@desy.de, Oct 2003

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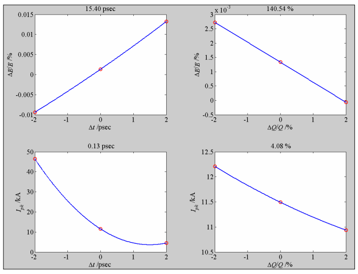
Scan gun-laser timing and charge, monitoring energy and peak current

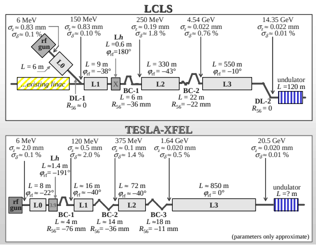


Set up timing jitter budget, compare LCLS and TESLA XFEL

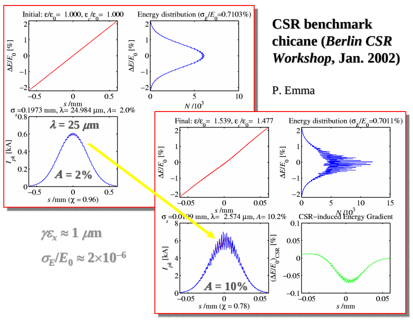
Table 2. A possible longitudinal jitter tolerance budget for LCLS and TESLA-XFEL.

$|\langle \Delta E/E_0 \rangle| < 0.1\%$ **and** $|\Delta I/I_0| < 12\%$

Parameter	Symbol	LCLS	$XFEL_2$	Unit
Gun timing jitter	Δt_0	0.80	1.5	psec
Initial bunch charge	$\Delta Q/Q_0$	2.0	10	%
mean L0 rf phase	φ_0	0.10	0.05	deg
mean L1 rf phase	φ_1	0.10	0.08	deg
mean L*h* rf phase 3.9-GHz & X-band	φ_h	0.50	0.07	*h*-deg
mean L2 rf phase	φ_2	0.07	0.10	deg
mean L3 rf phase	φ_3	0.15	1.0	deg
mean L0 rf voltage	$\Delta V_0/V_0$	0.10	0.08	%
mean L1 rf voltage	$\Delta V_1/V_1$	0.10	0.20	%
mean L*h* rf voltage	$\Delta V_h/V_h$	0.25	0.30	%
mean L2 rf voltage	$\Delta V_2/V_2$	0.10	0.20	%
mean L3 rf voltage	$\Delta V_3/V_3$	0.08	0.09	%



CSR driven Instabilities:



CSR benchmark chicane (*Berlin CSR Workshop*, Jan. 2002)

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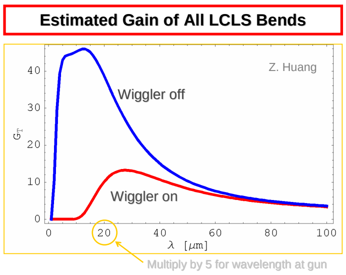
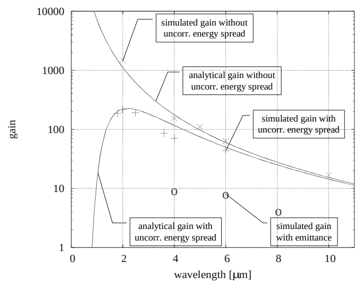


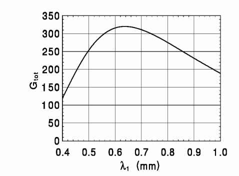
Gain curve for LCLS



Gain curve for XFEL

Space Charge Driven Instability:

E. Schneidmiller: Gain Curve for TTF-2 and Consequences



Total gain versus initial modulation wavelength

What happens next?

Assume initial modulation at the "optimal" wavelength to be 10-3. This results in 30 % density modulation at a wavelength of 10µm after BC2.

Consequences:

• Emittance growth in last dipole(s) of BC2

• LSC in BC2 to undulator section. For a final energy of 1 GeV the impedance is |Z|/Z0 = 200. That means about 4 MeV energy modulation (±2sigma). Also, local energy spread is growing.

Conclusion: for reliable operation of the facility one should keep initial modulations well below 10-3 level. Or suppress amplification.

What should we do?

Full S2E required (incl. plasma oscillations at low energy, CSR in BCs, other wake fields). Studies of noise sources in the gun.

Laser pulse should be as smooth as possible. One might even refuse the concept of flat-top pulse with small rise/fall time (which is good for projected emittance, but not necessarily for central slices).

Increasing Uncorrelated Energy Spread to Suppress Instability

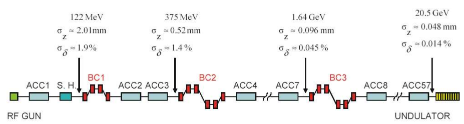
- Maximum gain is very sensitive to the local energy spread. Instability in TTF2 linac could be strongly suppressed if the initial energy spread would be 15-20 keV.
- LCLS: A super-conducting wiggler (at 4.5 GeV) is going to be used to control energy spread. This method does not work at relatively low energies.
- We suggest another method: FEL type modulation of the beam in optical wavelength range by a laser pulse in an undulator. Then the beam goes through the bunch compressor where these coherent energy modulations are quickly dissipated, leading to the effective "heating" of the beam. Similar mechanism takes place in storage ring FELs.

A numerical example for TTF2 (possibly for DESY-XFEL):

The undulator with ten periods, a period length 3 cm, and a peak field 0.49 T is located in front of

BC1. A fraction of power in the second harmonic ($\lambda = 0.52\mu m$) of the Nd:YLF laser is outcoupled from the photoinjector laser system and is transported to the undulator. For a transverse size of the laser beam 0.5 mm (Rayleigh length is 1.5 m) and a power of 300 kW, the amplitude of energy modulation will be about 20 keV (rms energy spread is smaller by √2).

S2E Status and Plans:



I.) ASTRA PARMELA — elegant — GENESIS FAST
(wake-fields, 1D CSR, no space charge)

II.) " CSRtrack in compressors, elegant in linac "
(wake-fields, 3D CSR, no space charge)

III.) " CSRtrack in compressors, ASTRA/PARMELA in linac "
(wake-fields, 3D CSR, space charge)

- **First complete S2E simulations for XFEL are done (Zeuthen benchmarking example)**
- **Need further study on the impact of CSR and space charge driven instabilities**
- **Will use S2E simulation to optimize jitter tolerances**

responsible author:
N.N., DESY
N.N@desy.de, Oct 2003