What should Start to End Simulations for Light Source ERLs be sure to include?

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Content:

- effects
- simulation codes
- start to end simulations

Storage Rings, LINACs and ERLs: variation in parameters

	Storage Rings	LINACs	ERLs
Mean path length / m	10^{13} (τ=10h)	10^{1} - 10^{4}	10^{1} – 10^{2}
Mean travel time / s	10^{4}	$<10^{-4}$	$<10^{-5}$
Norm. emittance / mm mrad	20 – 50 (hor.)	1 (0.1)	
Current / mA	10^{2}	<1	10^{2}
Bunch length (rms) / ps	10^{1}	10^{-2}	
Peak current / A	10^{1}	10^{3}	
Bunch charge / nC	0.1 -1		
Rel. energy spread (sliced)	10^{-3}	10^{-4}	

ERLs compared to Storage Rings:

- large fraction of beam path goes through cavities
- single pass devices: no (less – BBU) resonant behaviour → tracking procedures do not need to be as highly sophisticated as for Storage Rings

Potentially Disturbing Effects

With these parameters most relevant effects for ERLs can be identified already:

• **Space Charge:** high charge density due to both small transverse (low emittance) and small longitudinal (bunch length) dimensions → energy spread & emittance growth

special care for the injector: no accumulation like in Storage Rings -> full bunch charge in one single gun shot at lowest energies

• **Coherent Synchrotron Radiation CSR:** short pulses emit powerful coherent radiation at wavelength comparable to the bunch length; interaction of bunch with CSR-field → energy spread & emittance growth

• **Cavity Wakes:** bunches passing the cavities deposite energy in monopole or higher order modes (HOM) → energy change, energy spread & emittance growth, in resonance even total beam loss (BBU)

• **Resistive and Geometric Wakes:** most relevant for small vacuum chambers (undulator sections) → energy spread & emittance growth

• **Ion Trapping:** the strong potential of the electron current attracts positively charged ions (like in Storage Rings); ion potential causes additional focusing, scattering on ions → energy spread & emittance growth

Potentially Disturbing Effects

- **Incoherent Synchrotron Radiation:** only a minor effect at low energy ERLs, might lead to emittance and energy spread growth in high energy ERLs
- **Intra Beam Scattering:** build up times usually too long compared to beam travel time, can be relevant at extreme bunch densities

ERLs are used for various purposes: **which parameters are most important for which device?**

- **ERL-FELs:** high peak current, ultra low sliced energy spread and emittance – some tolerance in projected values
- **ERL-Light Sources:** like FEL but no hard limits
- **ERL-Cooler:** cooling most efficient at high electron current, low energy spread and emittance, sensitive to projected values
- **ERL-Collider:** high current and large emittance

Focus on FEL- and Light Source ERLs: observe sliced and projected energy spread and emittance of compressed bunches

Potentially Disturbing Effects

Next slides:

short introduction to the relevant effects that can be considered in single bunch Start-to-End (S2E) simulations.

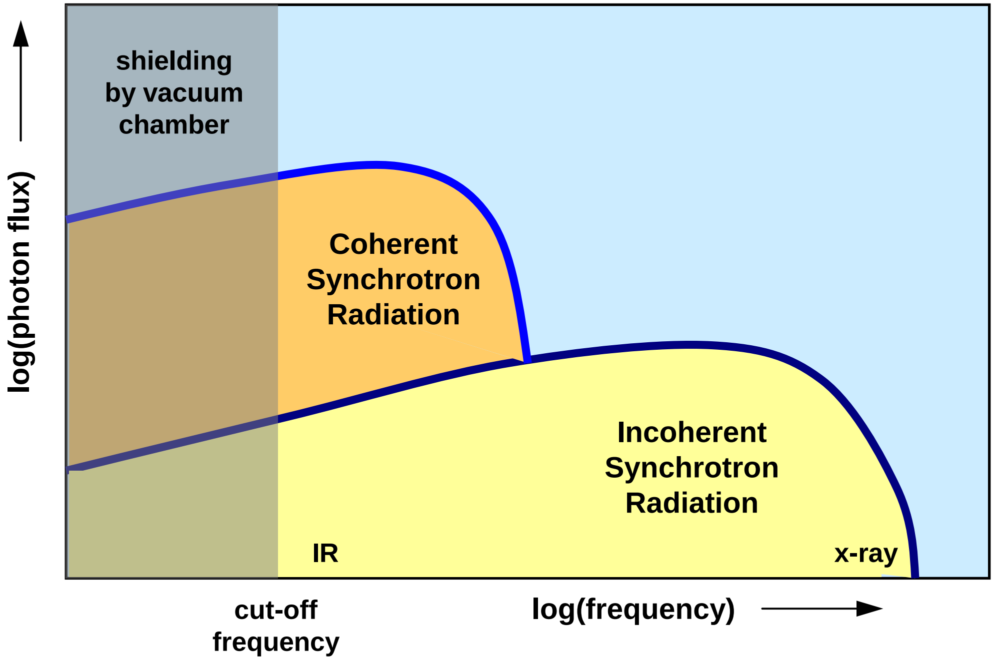
Note that the following effects are not considered:

- collective, multi bunch effects like BBU/Ion trapping: analytic formulas and simulation codes (e.g. ERLBBU, BI) to estimate current thresholds are available, but not implemented in the existing multi particle tracking codes
- FEL process: beam quality after FEL interaction must be good enough to allow for deceleration without particle losses – ask experts from WG 3 for this topic

Coherent Synchrotron Radiation CSR

- **Synchrotron radiation is usually emitted incoherently**
- **if $\sigma_l <= \lambda$ → Coherent emission of radiation: $P_{CSR}(f) = N\,P_0(f) + N^2\,P_0(f)\,F(f)$**

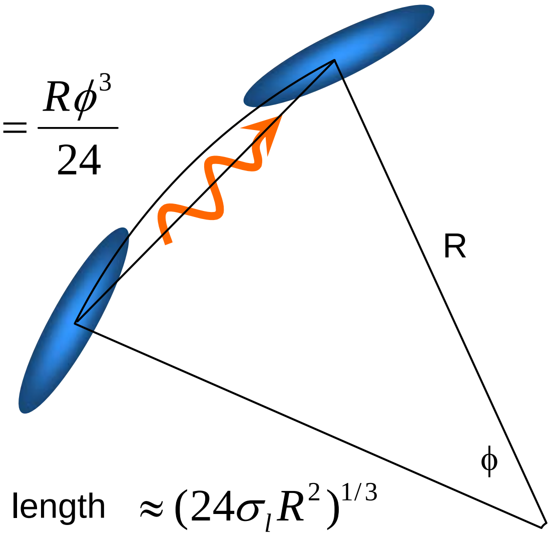
  P_0: P(single electron), F(f): form factor = FFT of longitudinal bunch charge density



- **ERLs: CSR can be emitted in dipole magnets of bunch compressors, 180 degree arcs, doglegs, …**

Coherent Synchrotron Radiation CSR

- **CSR fields from the tail of the bunch can catch up with the head**



slippage $= \dfrac{R\phi^3}{24}$

overtaking length $\approx (24\sigma_l R^2)^{1/3}$

CSR fields induce a momentum variation over the bunch

1D CSR wake: $$W(s) \sim \int_{s-R\phi^3/24}^{s} \frac{1}{(s-s')^{1/3}} \frac{\partial\lambda(s')}{\partial s'}\, ds'$$

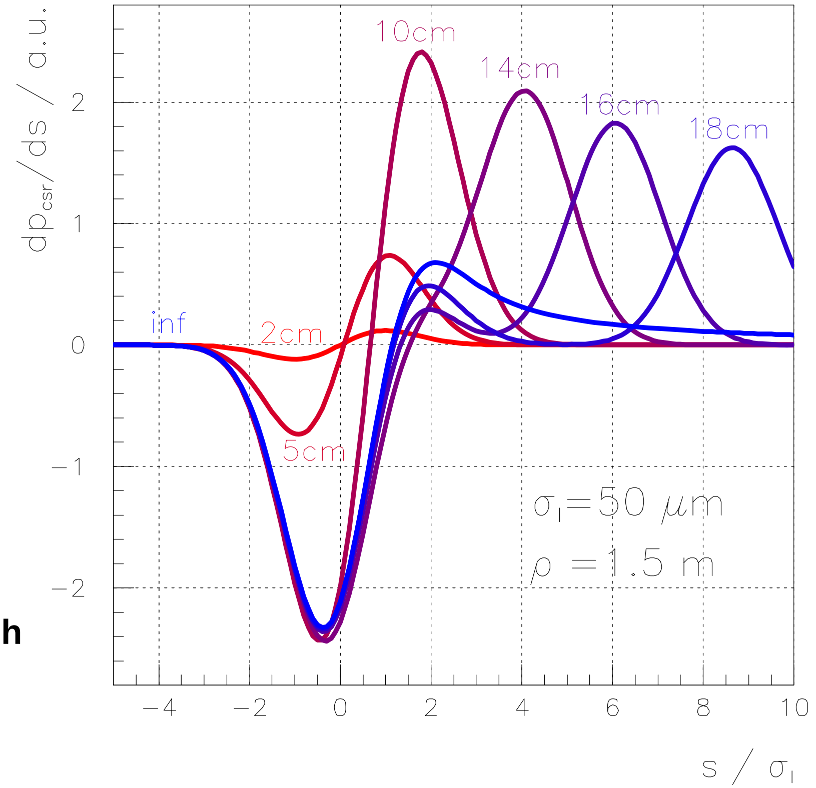


Fig.: 1D CSR wake for a Gaussian bunch at varying positions inside a dipole magnet

Coherent Synchrotron Radiation CSR

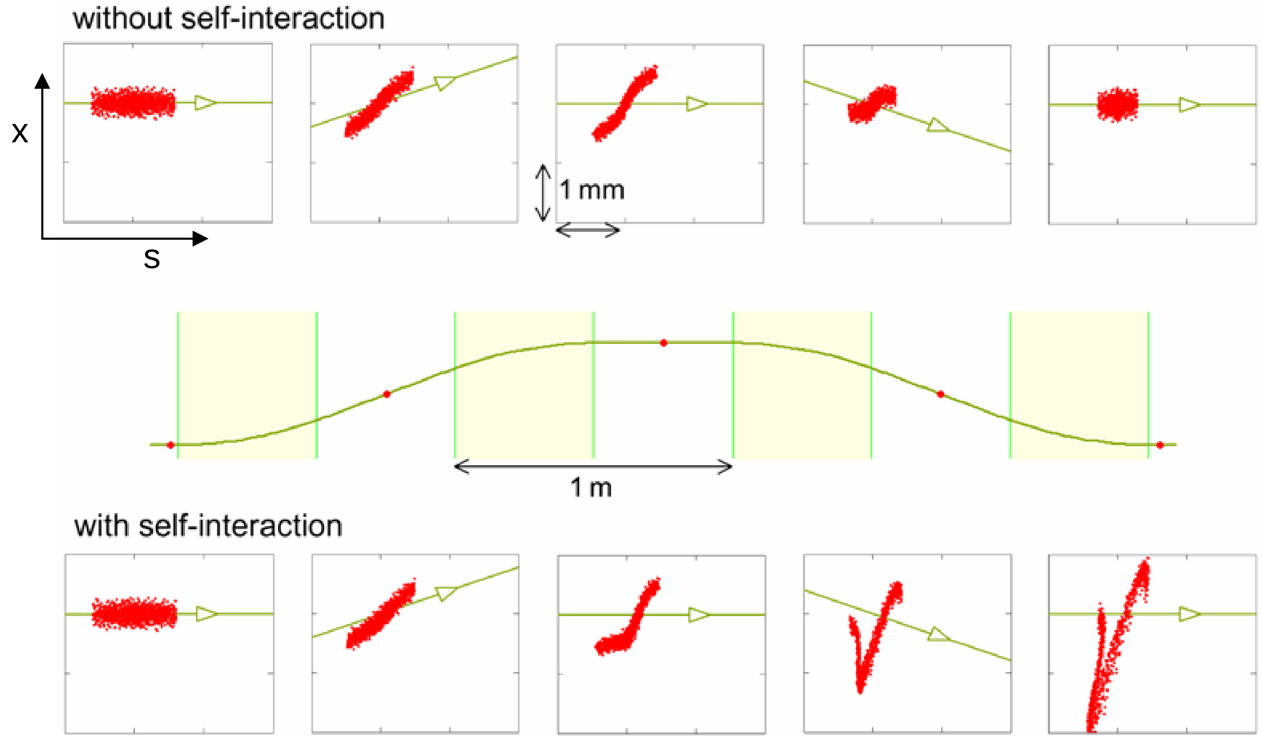


Fig.: x-s phase-space plots of a bunch pass-ing a four dipole chi-cane, with and without CSR

Courtesy of M. Dohlus

- CSR → energy modulation over the bunch
- energy modulation → growth of energy spread (correlated & sliced)
- energy modulation in dispersive sections → emittance growth (correlated & sliced)

Space Charge

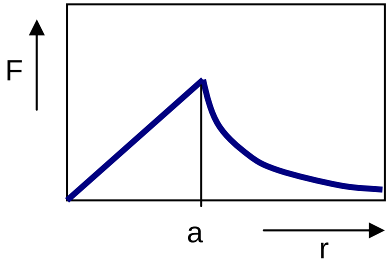
- electron bunch: cloud of 10^9 – 10^{10} charged particles with repulsive forces

$$\vec{F}(\vec{r}) = \frac{e^2}{4\pi\varepsilon_0} \sum_{l=1}^{N} \frac{\vec{r}-\vec{r}_l}{\left\|\vec{r}-\vec{r}_l\right\|^3} \qquad \vec{r} \neq \vec{r}_l \qquad \text{(static)}$$

Transverse Space Charge:

- simple example: round beam with radius a:

$$\vec{F}(\vec{r}) = \frac{2eI}{\gamma^2 v a^2}\vec{r}$$



- space charge in a drift acts like a quadrupole magnet, defocusing in both planes:

elliptic beam:

$$\frac{1}{F_x} = \frac{4I(s)}{(\gamma\beta)^3 I_A}\frac{L}{a(a+b)} = \underline{f(s)}$$

$a^2 = \varepsilon_x \beta_x$

$b^2 = \varepsilon_y \beta_y$

L: considered path length

I_A: Alfven current

growth of projected emittance:

$$\varepsilon_x = \varepsilon_{x_0}\sqrt{1+\beta_{x_0}^{\,2}\left(\left\langle\frac{1}{F_x^{\,2}}\right\rangle - \left\langle\frac{1}{F_x}\right\rangle^2\right)}$$

Longitudinal Space Charge (LSC)

- repulsive forces in direction of motion: particles in the bunch head gain energy, those in the tail lose energy

$\vec{E}(r,z,t)$ → induce momentum modulation → growth of energy spread

- at low energies: space charge oscillations

$$\omega_{LSC}{}^{2}(k) = c^{2}\,\frac{kI}{\gamma^{3}I_{A}}\,\frac{4\pi\left|Z_{LSC}(k)\right|}{Z_{0}}$$

on axis LSC impedance:

(round, uniform beam)

$$Z_{LSC}(k)=\frac{iZ_0}{\pi k r_b{}^2}\left[1-\frac{kr_b}{\gamma}K_1\left(\frac{kr_b}{\gamma}\right)\right]\underset{\substack{\uparrow\\ \frac{kr_b}{\gamma}<<1}}{\approx}\frac{iZ_0k}{4\pi\gamma^2}\left(1+2\ln\frac{\gamma}{kr_b}\right)$$

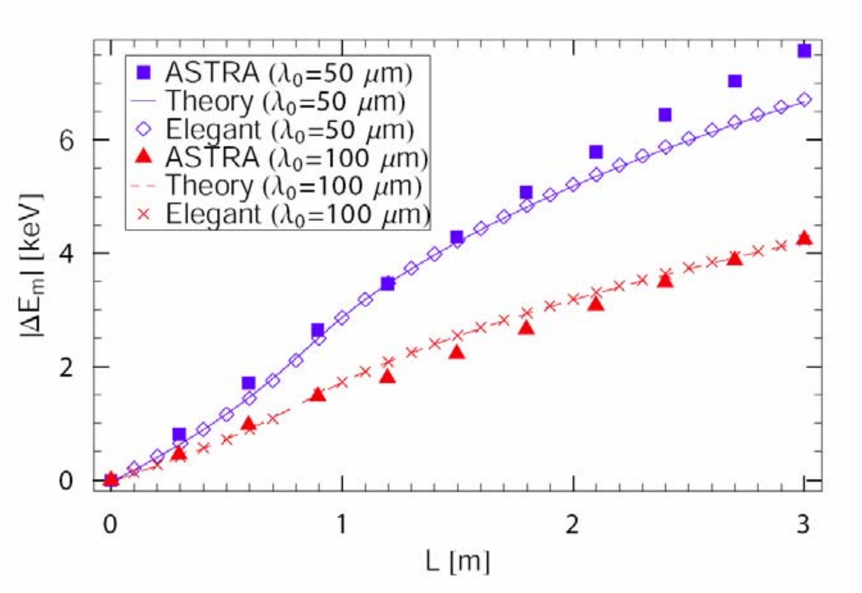


Fig: LSC-induced energy modulation amplitude in a drift section E=120 MeV, I=120 A, ±5% initial density modulation at 50/100 µm.

Courtesy of Z. Huang

Microbunching Instability

- LSC in combination with CSR: microbunching instability

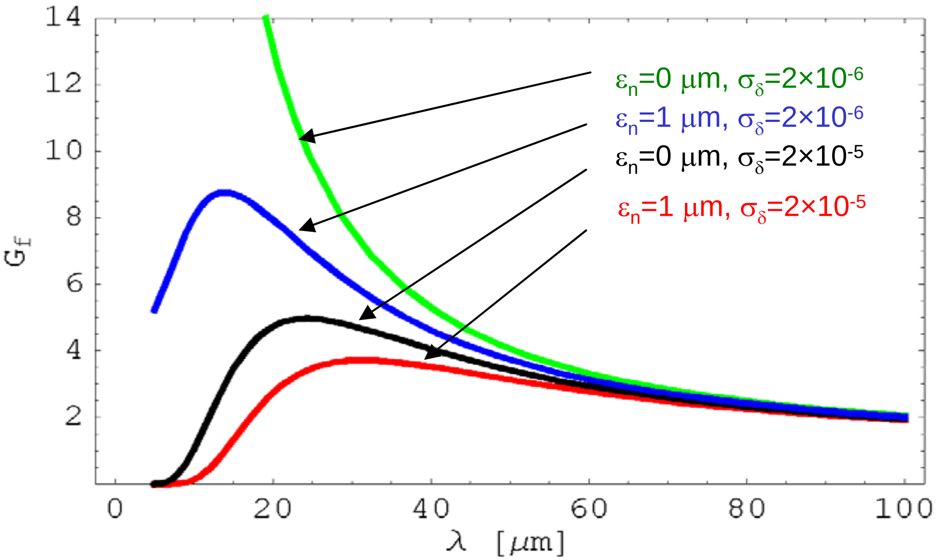
small charge density modulation from the injector (e.g. due to modulation of photo-cathode laser power)

→ LSC induces momentum variation

→ momentum modulation transforms to density modulation (by LSC oscillations at low energy or in dispersive sections)

→ density modulation is source of strong CSR fields in compressors etc.

→ CSR induces additional momentum modulation, possibly increasing the initial one



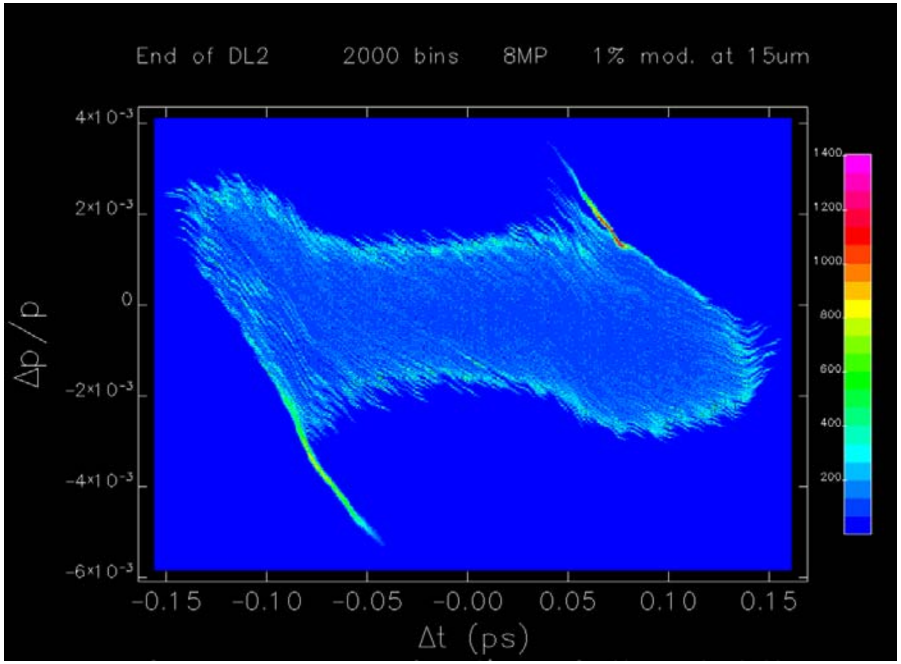
$$\text{Microbunching Gain: } \frac{\text{Final bunching factor } b_f(k_f)}{\text{Initial bunching factor } b_0(k_0)}$$

$$b(k) = \frac{1}{Nec}\int I(z)e^{-ikz}dz$$

Fig.: CSR microbunching gain for the CSR2002 workshop benchmark case (chicane @ 5 GeV) as a function of the initial density modulation wavelength.

Courtesy of Z. Huang

Microbunching Instability



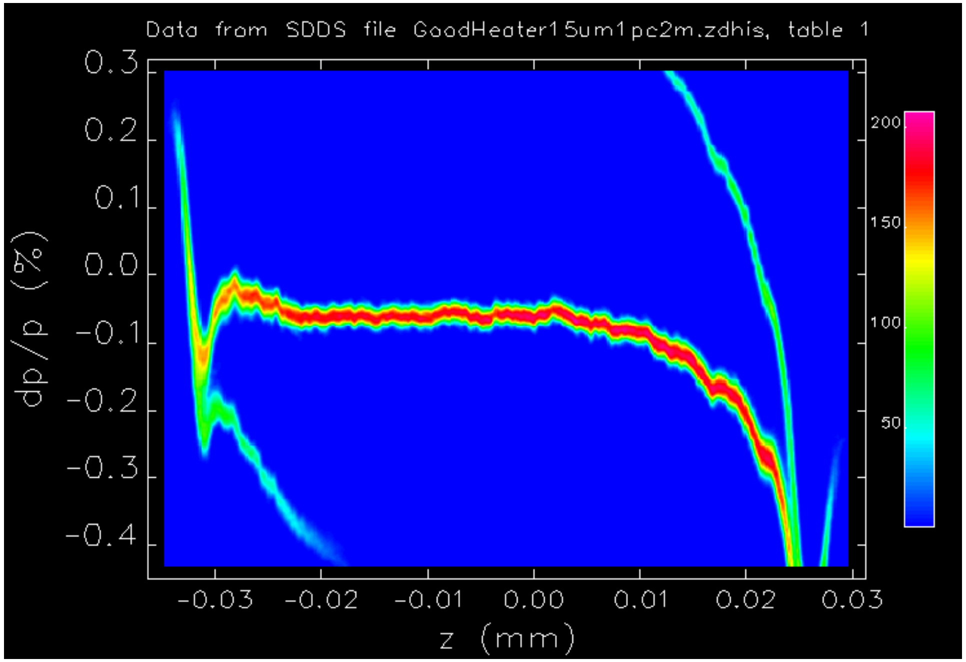
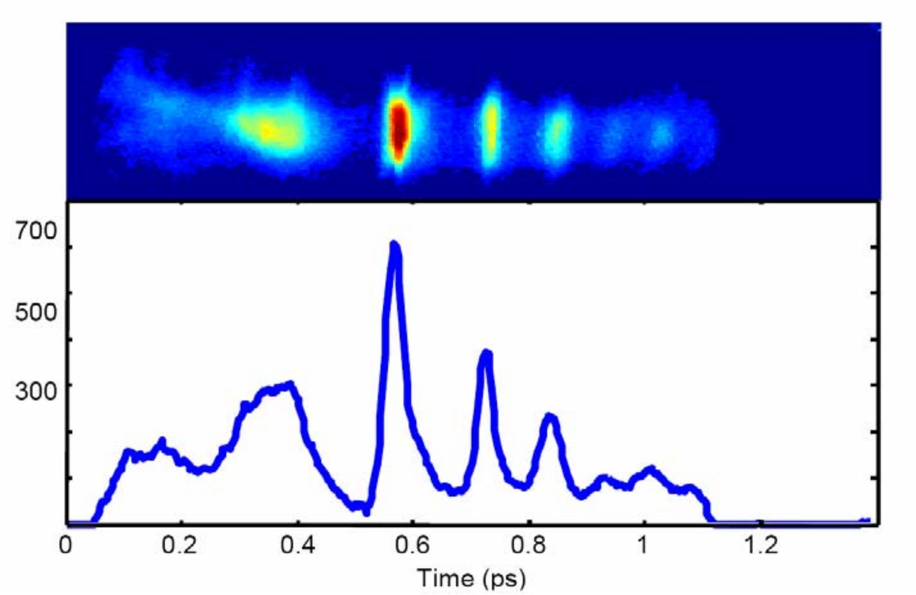


Fig.: simulated LCLS longitudinal phase space at the end of DL2 with 1% initial density modulation at 15 μm without a laser heater.

Courtesy of Z. Huang, M. Borland

Fig.: like before (figure on the left) but this time with the laser heater.

Microbunching Instability



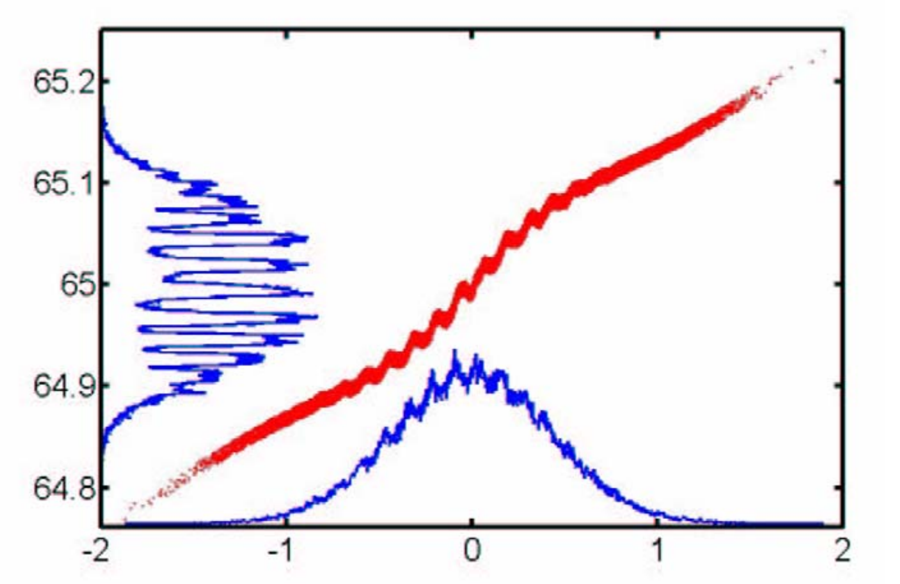


Fig.: momentum distribution after bunch compressor measured at the DUV-FEL (hor. axis corresponds to momentum).

Courtesy of T. Shaftan

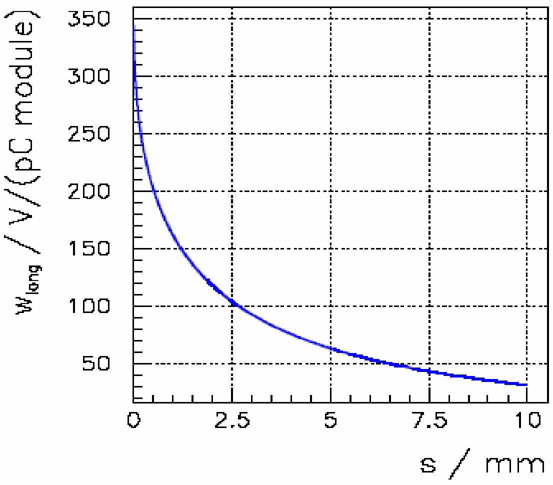
Fig.: simulated longitudinal phase space with projections of the DUV-FEL (after bunch compressor)

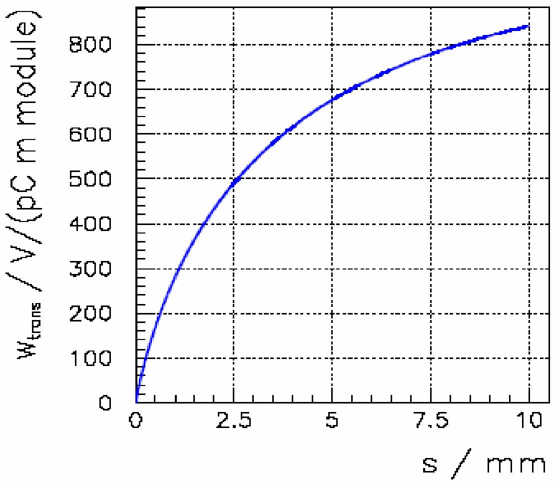
Cavity Wake Fields

- bunches deposit power in the cavities → cavity wake fields (beam loading both to fundamental and to HOMs)
- effects are considered in different time scales: single bunch and multi bunch effects (BBU)

Single Bunch Effects:

- wake field varies over the bunch length → bunch energy is modulated (long. wakes) and emittance can be increased (transv. wakes)
- wake functions: simulations give empirical analytical expression, e.g. TESLA module (8 cavities)





$$w_{\parallel}(s) = 344\exp\left(-\sqrt{\frac{s}{s_0}}\right)$$

$$w_{\perp}(s) = 10^3\left(1-\left(1+\sqrt{\frac{s}{s_1}}\right)\exp\left(-\sqrt{\frac{s}{s_1}}\right)\right)$$

$$W(s) = \int_{-\infty}^{\infty} w(s')\lambda(s-s')ds'$$

Resistive & Geometric Wakes

- **Resistive Wall Wakes:** longitudinal wake for a round pipe of radius a, (dc) conductivity σ

$$W(s) = \frac{4Z_0 c}{\pi a^2}\left(\frac{e^{-s/s_0}}{3}\cos\frac{\sqrt{3}s}{s_0} - \frac{\sqrt{2}}{\pi}\int_0^\infty \frac{dx\, x^2 e^{-x^2 s/s_0}}{x^6+8}\right) \qquad s_0 = \left(\frac{2a^2}{Z_0\sigma}\right)^{\frac{1}{3}}$$

- analog expression for the transverse resistive wake

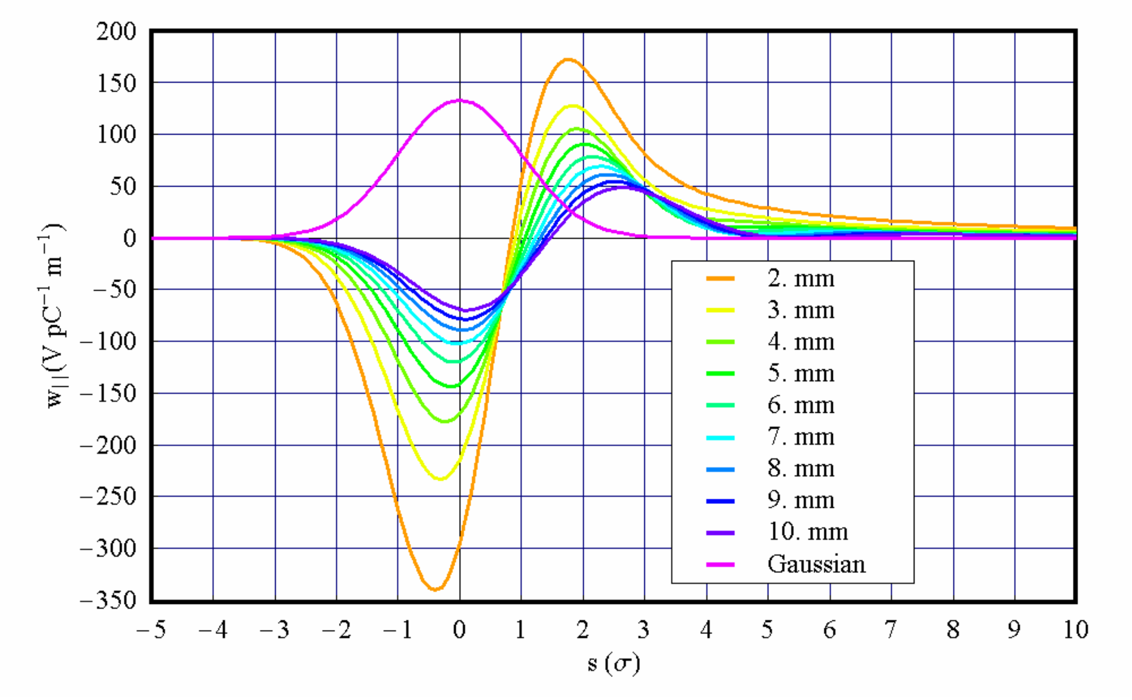


Fig.: longitudinal wake potential for a Gaussian bunch for different copper vessel internal radii.

Q = 1 nC, σ_t = 50 fs

Courtesy of H. Owen

Resistive & Geometric Wakes

- **Surface Roughness Wakes:** small cavity-like structures

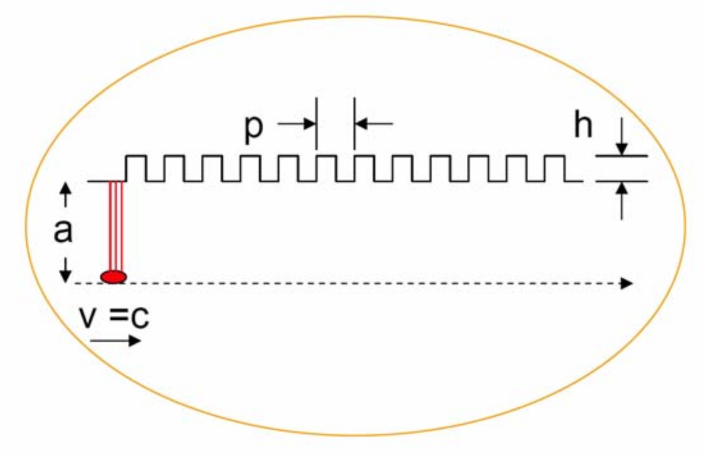
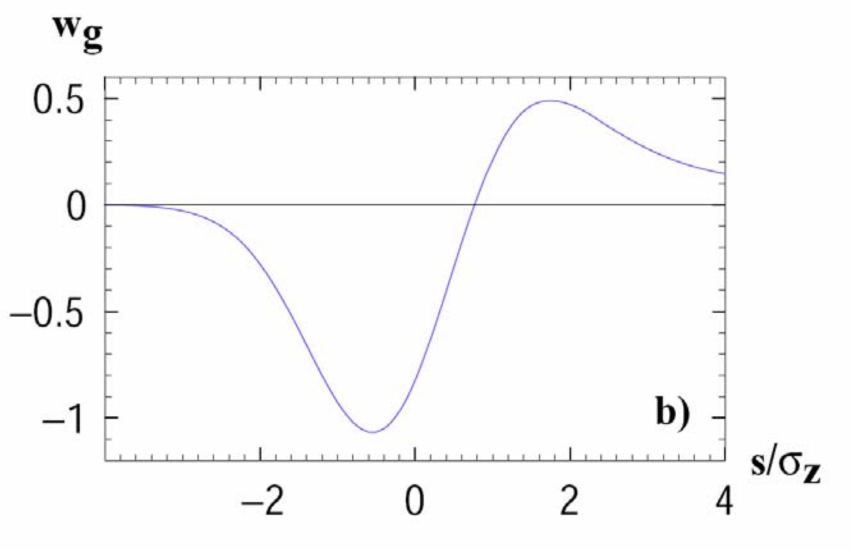


Fig. (left): Geometry for the "small corrugations model" of roughness impedance.

Fig.(bottom): wake of shallow, periodic corrugations for a Gaussian bunch: h<<p<<a, σ_l <k_1

Courtesy of K. Bane



$$W(s) = \frac{Z_0 c h^2 k_1^{\ 3}}{4\pi a} f(k_1 s)$$

$$k_1 = 2\pi / p \qquad f(x) = \frac{1}{2\sqrt{\pi}} \frac{\partial}{\partial x} \frac{\cos(x/2) + \sin(x/2)}{\sqrt{x}}$$

$$W(s) = -\frac{Z_0 c h^2}{16\pi^{3/2} a} \left(\frac{k_1}{s}\right)^{3/2} \qquad \text{for} \quad \sigma_l <\approx k_1$$

Simulation Codes: Space Charge

C. Limborg et al: "Code Comparison for Simulations of Photo-Injectors", PAC03:

- various codes with various approaches (even more than compared here: GPT, BEAMPATH, ITACA, …)

code	Algorithm	?D	SC calculated from	comput. time
HOMDYN	solving envelope equation (semi-analytical)	2D	one uniformly charged cylinder	short
PARMELA	Lorentz transformed space charge forces	2D	uniformly charged rings	long
ASTRA				medium
PARMELA SPCH3D	fast Particle-in-Cell	3D	macro particles	long
TREDI	retarded potentials, Lienard-Wiechert	3D	macro particles	long

- Simulation results: good agreement inside gun – some disagreement in drift (HOMDYN)
- Thermal emittance: initial distribution can be defined in all codes, **no code includes physics behind**
- Shottky effect: only considered by ASTRA
- Longitudinal profile: all codes but HOMDYN
- Transverse non-uniformity: 3D codes, ASTRA upgraded

Simulation Codes: CSR

- again, various codes with various approaches:
    - 1D: ELEGANT, CSR-Calc, CSR-Track (1D option): CSR effects calculated from long. charge density, fast
    - 3D: CSR-Track / TraFiC^4, TREDI, slow

ELEGANT:
- fully equipped 3D optics simulation tool with macro-particle tracking
- special dipole and drift elements added to include CSR effects in 1D appraoch
- transverse and longitudinal wake fields can be applied
- LSC elements included

CSR-Track / TraFiC^4:
- 1D option like in ELEGANT
- Green's function method for fast 3D simulations
- „direct method" for many particles combining Green's function method with meshed field method

TREDI:
- Lienard-Wiechert potentials approach (also for space charge effects)

ICFA CSR workshop, DESY-Zeuthen, 2002 : reasonable agreement between codes (exception: TREDI)

Simulation Codes: Combine Codes for Start-to-End Simulations

How to combine codes? How can output(code1) be transformed to input(code2)?

- often parametrization of bunch is done. Potentially neglected: a) correlations between phase space dimensions e.g. momentum chirp b) parameter variations over the bunch length (sliced values)
- better: 6D macro particle phase space is easy to share between codes. Sometimes a problem: adjusting number of particles

→ select codes for Start-to-End simulations also with respect to their abilities to share the bunch data between the programs

- In the last years: S2E simulations for LCLS, TTF, X-FEL, BESSY-FEL, …

the following codes have often been used:

PARMELA/ASTRA → for space charge dominated machine parts (gun, low energy sections)

ELEGANT/CSR-Track/CSR-calc → dispersive sections (bunch compressors, arcs, doglegs)

GENESIS/FAST/GINGER/MEDUSA → FEL process

- first attempts for master programs controlling all involved codes: GlueTrack (Zagorodnov, DESY) combining ASTRA, CSR-Track and GENESIS
- individual solutions: ASTRA → ELEGANT: script using tools from SDDSToolkit

ELEGANT → GENESIS: SDDSToolkit program „elegant2genesis“

Summary

- Quality of the electron bunches has to be conserved during beam transport, acceleration, compression and all other manipulations

- Most relevant (single bunch) effects with the potential to deteriorate bunch quality: space charge and CSR fields, cavity wakes, resistive wall and geometric wakes

- Simulation codes for each of these effects are available but no code that includes all

- For Start-to-End simulations output-input conversion has to be done very carefully: 6D macro particle phase space best suited. With parametrizations: correlations in phase space have to be included