Wakefield Studies for a Bunch Arrival-Time Monitor Concept with Rod-Shaped Pickups on a Printed Circuit Board for X-ray Free-Electron Lasers

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MOTIVATION

The European XFEL (EuXFEL) and other notable X-ray Free-Electron Laser facilities rely on an all-optical synchronization system with electro-optical bunch arrival-time monitors (BAM). The current BAMs were benchmarked with a resolution of 3.5 fs for nominal 250 pC bunches at the EuXFEL, including jitter of the optical reference system. The arrival-time jitter could be reduced to about 10 fs with a beam-based feedback system. For future experiments at the EuXFEL the bunch charge will be decreased to a level where the existing system's accuracy will no longer be sufficient. In simulations a concept based on rod-shaped pickups mounted on a printed circuit board indicated its potential for such low charge applications. For the feasibility of the proposed design, its contribution to the total impedance is essential. **In this work the design and an intermediate version are compared to state-of-the-art BAM regarding their wake potential. Furthermore, measures to mitigate wakefields are discussed.**

SIMULATION MODELS

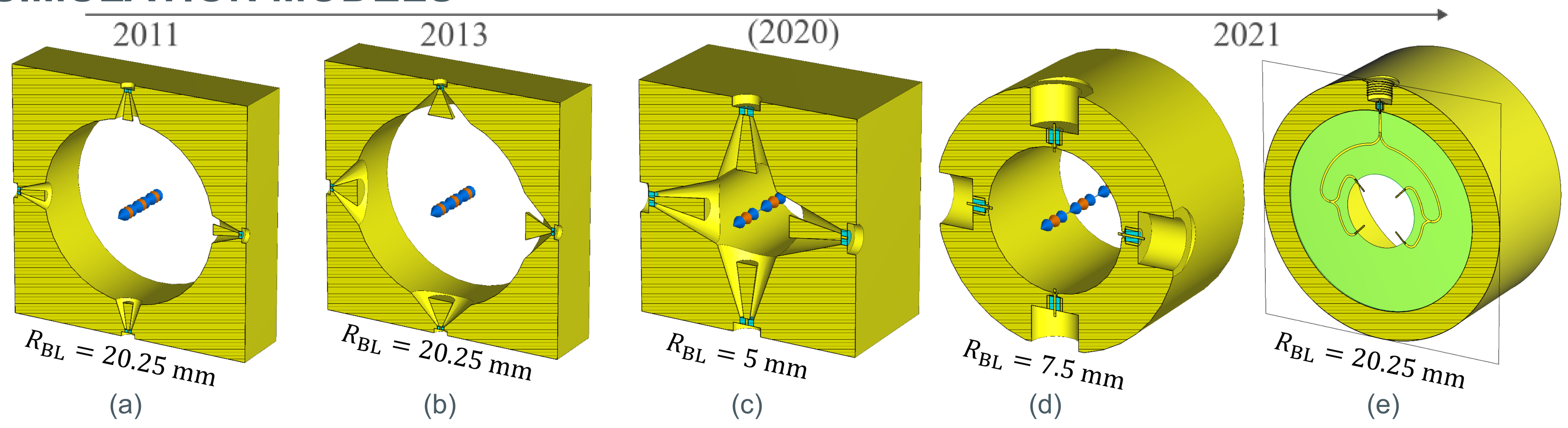

Figure 1: Designs used for wakefield analysis. The parameter can be found in the corresponding publications.

Fig. 1a:	1st generation cone-shaped pickups, proposed for the BAM in 2011 in [1]
Fig. 1b:	2nd generation cone-shaped pickups, proposed 2013 in [2]
Fig. 1c:	1st generation pickups scaled to $R_{\mathrm{BL}} = 5$ mm, as discussed in [3]
Fig. 1d:	Rod-shaped/open-coax demonstrator, published in [4]
Fig. 1c:	Pickup structure with rods on a printed circuit board (rPCB), published in [4]

WAKEFIELDS

Interaction of charged particle with surroundings, caused by finite conductivity & geometric changes and described by:

- Wake function $w_\parallel$ (by pulse excitation)
- Wake potential $W_\parallel$ (by bunch)
- Wake impedance $Z_\parallel = (\mathcal{F}\, W_\parallel)(\omega)$
- Wake loss factor (WLF) k_σ
- Energy spread factor (ESF) = rms energy spread per charge

$$w_\parallel(z) = \frac{1}{q}\int_{-\infty}^{\infty} E_z(r_0, s, r, z)\,\mathrm{d}s$$

$$W_\parallel(z) = \frac{1}{Q_B}(w_\parallel * \lambda)(z) \qquad k_\sigma = \frac{1}{Q_B}\int_{-\infty}^{\infty}\lambda(z) W_\parallel(z)\mathrm{d}z$$

$$ESF(\sigma) = \sqrt{\frac{1}{Q_B}\int_{-\infty}^{\infty}\lambda(z)[W_\parallel(z) + k_\sigma]^2\mathrm{d}z}$$

[5-9]

SIMULATION [10]

Wakefield solver of CST Particle Studio® [7, 10]

- Direct calculation of $W_\parallel(z)$
- Single sided DFT → $Z_\parallel$
- Calculation of k_σ from $W_\parallel(z)$

Configuration:

- Indirect interfaces, wakelength > 300 mm
- mm-bunches

LONG RANGE WAKEFIELDS

Long range wakes were observed in the scaled 1st gen. BAM:

- Impedance peak at 21.9 GHz
- Relaxation length ≈ 32.2 m (half of EuXFEL's bunch spacing)
- Caused by a trapped mode [7, 11, 12]: **TM_{01}**
- Will not impair the voltage signal, but potentially next bunch.

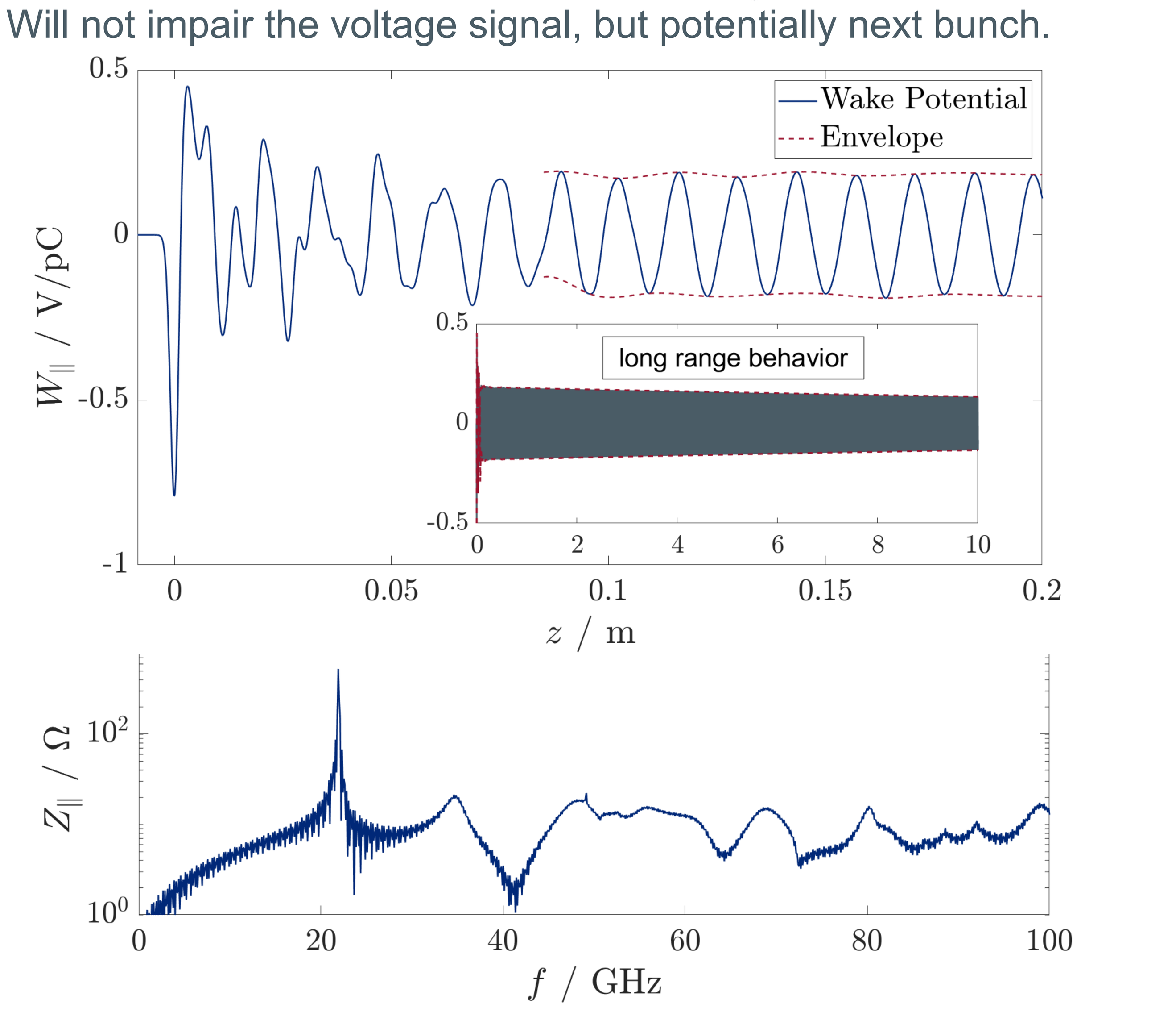

Figure 2: Simulated $W_\parallel$ (top) and $Z_\parallel$ (bottom) of 1st gen. pickups with $R_{\mathrm{BL}} = 5$ mm. The simulation was executed with 1 pC, 1 mm bunch and 10 m wakelength.

WAKE LOSS FACTOR

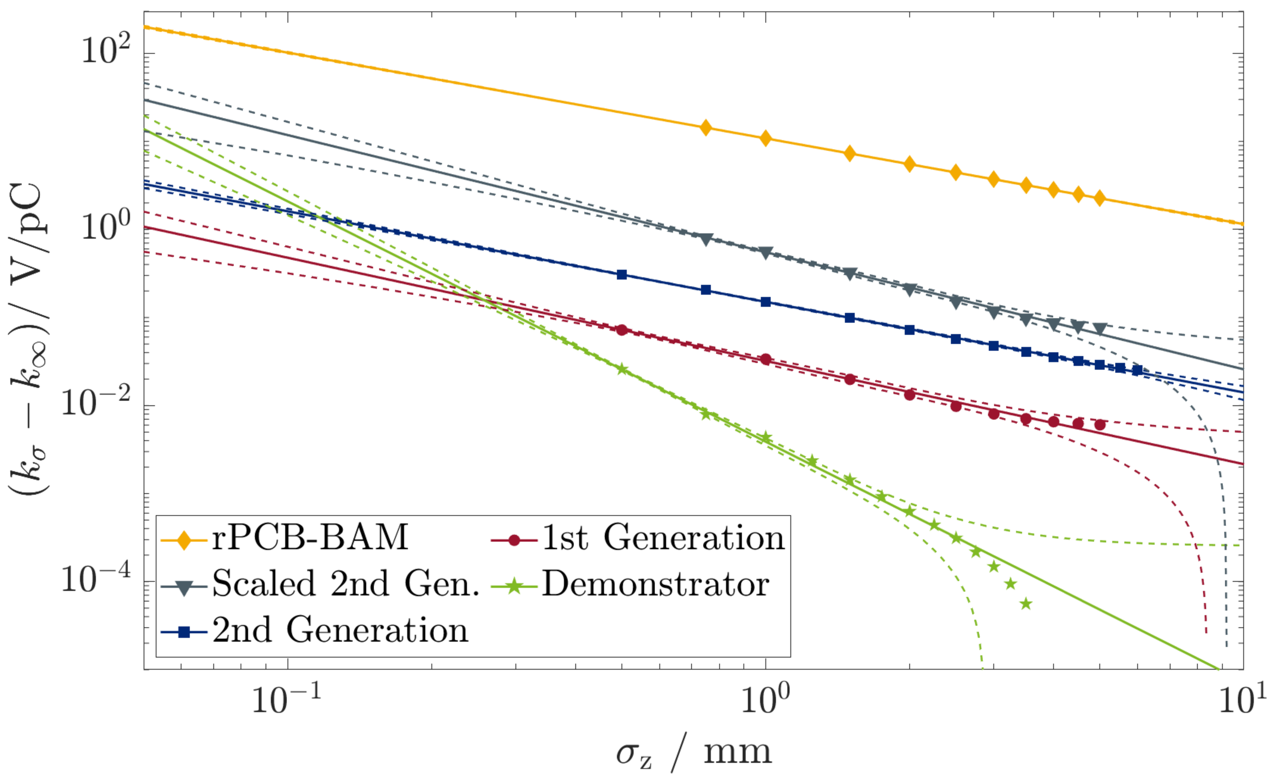

Figure 3: Log-log plot of the total WLF as a function of bunch length for different geometries. Symbols indicate CST® simulation results, solid lines a power law fit, and dashed lines are the 99 % PI.

Fit by a power law and extrapolation to sub-mm [13-15]

$$k_\sigma = \hat{K}\cdot\left({}^{\sigma_z}/_{1\,\mathrm{mm}}\right)^{-\alpha} + k_\infty$$

	α	$k_{1\mathrm{mm}}$ V/pC	k_{180fs} V/pC
rPCB	0.97	9.665	185.07
sc. 1st Gen.	1.33	0.483	26.79
2nd Gen.	1.03	0.132	3.02
1st Gen.	1.17	0.027	0.98
Demo.	2.73	0.004	11.24

rPCB BAM:

- $ESF(1\mathrm{mm}) \approx 4.15\ {}^{\mathrm{V}}/_{\mathrm{pC}}$
- Behaves like a collimator $k_\sigma \approx \frac{Z_0}{2\sqrt{\pi^3}}\frac{c_0}{\sigma_z}\ln\left(\frac{R_{\mathrm{BL}}}{R}\right)$ [7]

WAKEFIELD MITIGATION

For the rPCB wakefield reduction is worthwhile.

Integration into a collimator

- No additional transition
- Shielding from beam
- Possible background noise
- Space limitation and moving parts

Quasi-coaxial transmission line (TL) and holes

- WLF Reduction ≈ 40 %
- Broken symmetry
- Slight decrease of the voltage signal

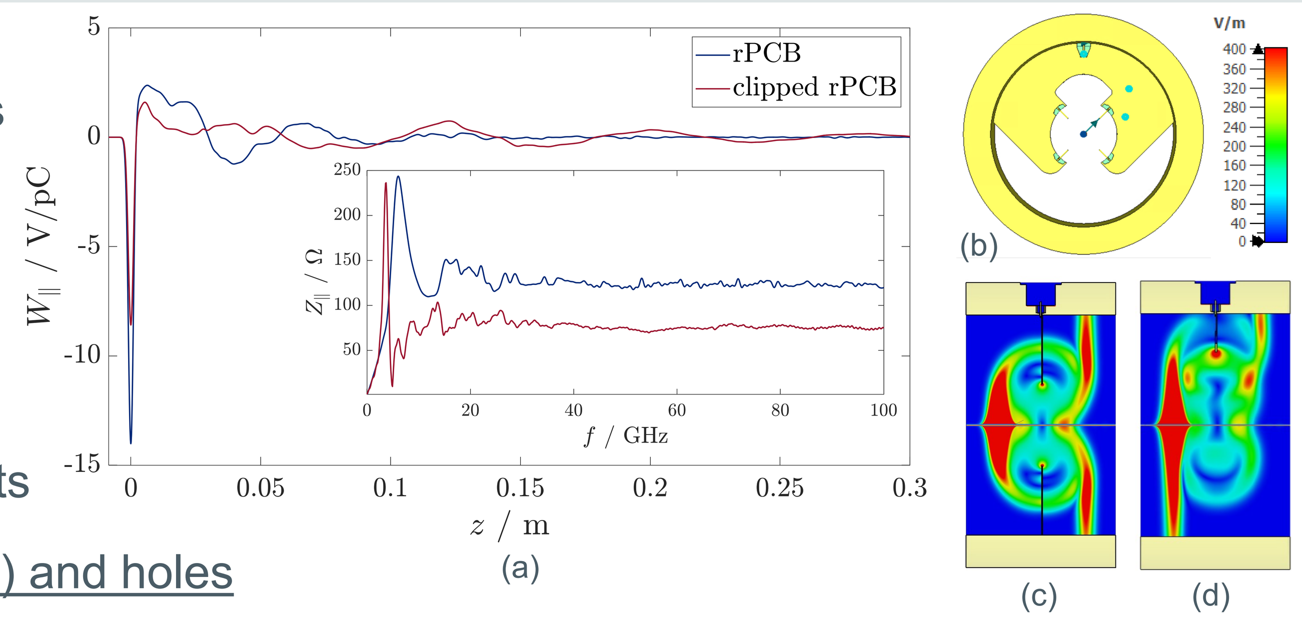

Figure 4: Wake potential and impedance of a regular and clipped rPCB (a), CST model (top right) and sideview (cut at the center) of the electric field after passing full (c) and reduced (d) rPCB.

CONCLUSION

- Substantial WLF for the rPCB design
- rPCB can be treated as a collimator
- Wakefields may be tolerable
- Some prevention methods are promising, but must be analyzed for cost-benefit ratio

OUTLOOK

- Address viability of the design
- View transverse wakefields
- Assess optimal realization regarding maximum signal strength and low effect on the beam

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