CURRENT FEL PHYSICS RESEARCH AT SLAC*

G. Stupakov, SLAC National Accelerator Laboratory, Menlo Park, CA, USA

Abstract

In this paper we review several techniques being pursued at SLAC National Accelerator Laborary with the goal of improving the longitudinal coherence and increasing the output power of x-ray FELs. They include echo enabled harmonic generation (EEHG), hard x-ray self-seeding, using undulator tapering to increase the FEL power, and noise suppression in the electron beam.

INTRODUCTION

Free electron lasers (FELs) can provide tunable high-power coherent radiation which is enabling forefront science in various areas. At x-ray wavelengths, most of the FELs operate in the self-amplified spontaneous emission (SASE) mode [1, 2]. The Linac Coherent Light Source (LCLS) at SLAC working in the SASE mode at hard x-ray wavelengths [3] marked the beginning of a new era of x-ray science [4–6]. However, since SASE FEL radiation starts from beam shot noise, the FEL output has limited temporal coherence (i.e. noisy in both temporal profile and spectrum). FELs with improved temporal coherence (i.e. a well-controlled pulse shape and a bandwidth close to transform limit) should benefit many applications and enable new capabilities in many disciplines.

Various techniques [7–13] have been proposed to improve the FEL temporal coherence. In the self-seeding scheme, a monochromator is used to purify the spectrum of a SASE FEL and an additional undulator is employed to amplify the quasi-monochromatic radiation to GW level. Alternatively, seeding with an external source generated from an external laser may provide a fully coherent output having well-defined timing with respect to the laser. One way to directly seed an FEL is to use the high harmonic generation (HHG) source generated when a high power laser is injected to a noble gas.

EEHG SEEDING

To circumvent the need for a high power laser at short wavelength, frequency up-conversion techniques [10–14] have been envisioned to convert the external seed to shorter wavelengths. In the classic high-gain harmonic generation (HGHG), a single modulator-chicane system is used to bunch the beam at a harmonic frequency of the seed laser [10].

* Work supported by the U.S. Department of Energy under contract DE-AC02-76SF00515.

The frequency multiplication efficiency can be greatly improved with the recently proposed echo-enabled harmonic generation (EEHG) technique [12, 13]. In this scheme, an electron beam is first energy modulated by a laser with wave number k_1 and then sent through a chicane with strong momentum compaction after which the modulation is macroscopically smeared. Simultaneously, separated energy bands with a spread much smaller than the initial energy spread are introduced into the beam phase space. It turns out that if a second laser with wave number k_2 (k_2 can equal k_1) is further used to modulate the beam, after passing through a second chicane, density modulation at the wave number

$$k_E = nk_1 + mk_2 \tag{1}$$

can be generated (n and m are integers). The key advantage of EEHG is that by trading the large energy modulation from a laser with a large momentum compaction from a chicane, high harmonics can be generated from those separated energy bands with a relatively small energy modulation. Thus it promises both bunching and gain at very high harmonics, allowing the generation of coherent soft x-rays directly from a UV seed laser in a single stage.

The advanced frequency up-conversion efficiency has stimulated a broad interest in using the EEHG scheme to seed x-ray FELs [15–18]. In recent proof-of-principle experiments performed at SLAC's Next Linear Collider Test Accelerator (NLCTA) [14] and the SDUV-FEL at SINAP [19], the 4th and 3rd harmonics from EEHG have been observed. They demonstrated that a long-term memory of the beam phase space correlations could be properly controlled and preserved in the experiment. The latest results from the NLCTA presented the first evidence of 7th harmonics from the EEHG technique [20].

The novelty of the experiment [20] is that an rf transverse cavity (TCAV) was used to increase the slice energy spread by one order of magnitude such that the ratio of energy modulation to energy spread is similar to that in real seeded x-ray FELs. In this experiment, the 7th harmonic of the second laser at 227 nm was generated when the energy modulation is approximately $2 \sim 3$ times the slice energy spread.

The parameters of the experiment [20] are listed in Table 1.

Representative spectra of beam radiation after the seeding for various TCAV voltage are shown in Fig. 1. Fig. 1(a) through Fig. 1(d) show the HGHG spectra obtained with only the 1590 nm laser on, and Fig. 1(e) was obtained with

ISBN 978-3-95450-125-0

Table 1: Parameters of the ECHO-7 NLCTA experiment.

Electron beam energy	120 MeV
Bunch length	0.5-2.5 ps
Bunch charge	20-40 pC
Normalized emittance	$\sim 8\,\mu$m
Slice energy spread	~ 1 keV
First laser wavelength	795 nm
Second laser wavelength	1590 nm

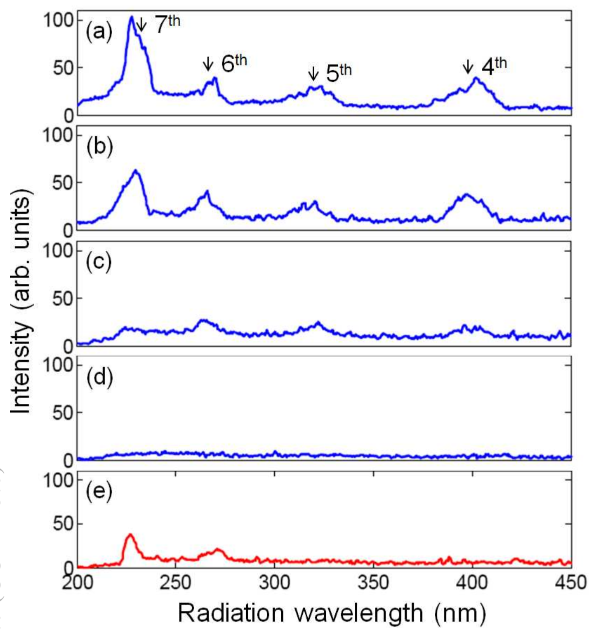

Figure 1: Spectrum of the radiation for various TCAV1 voltage:(a) V=0; (b) V=85 kV; (c) V=170 kV; (d) V=255 kV. The beam slice energy spread increases as we increase TCAV1 voltage. (a)-(d) are the HGHG signals when only the 1590 nm laser is on and (e) is EEHG signal at V=255 kV with both lasers on.

both lasers on. The spectrum of the coherent radiation is broadened due to the relatively large residual energy curvature from the varying rf phase along the bunch. As can be seen from Fig. 1, the harmonic radiation intensity decreases as TCAV voltage is increased. When the TCAV voltage was increased to 255 kV, the 4th to 7th harmonics were all suppressed and only the incoherent radiation was observed (Fig. 1(d)). When the first seed laser at 795 nm was turned on, the 7th harmonic was brought back.

The experiment [20] has presented the first evidence of high harmonics from the EEHG technique which overcomes the limit arising from the beam slice energy spread. It showed a clear signature that by splitting the phase space with a large momentum compaction chicane, high harmonics can be generated with relatively small energy modulation.

HARD X-RAY SELF SEEDING EXPERIMENT AT LCLS

While external laser-based seeding looks promising in the UV range and for soft x-rays, its usage for hard x-ray FELs creates extraordinary challenges and is not envisioned in the nearest future. Because of the difficulties of the direct seeding, the idea of self-seeding was proposed at DESY [7, 21]. It uses the SASE radiation generated in the first half of the undulator operating in a linear regime. An x-ray monochromator is installed between the first and the second halves of the undulators with a bypass for the electron beam. At the exit of the monochromator a narrow-band x-ray beam is combined with the electron beam and serves as a seed for the second half of the undulator.

The problem with this setup is that a typical monochromator delays the x-rays by several picoseconds. The electron beam has to be similarly delayed, requiring strong dipole magnets in the chicane of the bypass line. Incoherent synchrotron radiation and associated with it energy diffusion generate large energy spread in the beam which can suppress the FEL gain in the second half of the undulator. One of the approaches to overcome this difficulty was proposed in Refs. [22, 23]: it uses two bunches with the seed generated by the first one synchronized with the second bunch.

In another paper [24], the authors proposed to use a single diamond crystal in forward Bragg diffraction (FBD) geometry. They observed that due to the reflection of a narrow-band spectral line by the crystal, the transmitted x-ray pulses have a monochromatic tail (wake). While duration of the wake is relatively short (typically in the range of tens of femtoseconds) operation in a low-charge mode with extremely short bunches allows for the overlapping of the delayed bunch with the wake, which serves as a seed in the second part of the undulator. A detailed theory of the monochromatic wake formation is developed in [25].

Experimental demonstration of the crystal-based self seeding has been recently demonstrated at LCLS [26].

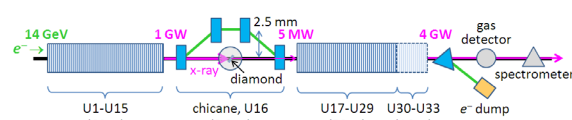

Figure 2: Layout of the LCLS undulator with a self-seeding chicane, diamond monochromator, gas detector and hard-X-ray spectrometer (from [26]).

In the experiment, a 110-μm thick diamond crystal, with a (004) lattice orientation, provided by the Technological Institute for Superhard and Novel Carbon Materials (Troitsk, Russia), was installed in place of one of the undulators. A new 3.2-m long magnetic chicane was added to the system to displace electrons transversely in order to bypass the diamond. The experiment demonstrated a dramatic narrowing of the spectrum from 20-eV FWHM

ISBN 978-3-95450-125-0

bandwidth to about 0.4-0.5 eV. The detailed account of the experiment can be found in Ref. [26].

TOWARD TERAWATT FEL

Using a crystal monochromator in the self-seeding scheme in combination with undulator tapering allows one to considerably increase the FEL output power. The underlying method is due to Kroll, Rosenbluth, and Morton (KLM) [27]. It relies on the increase of the energy transfer from the electrons to radiation by adjusting the undulator magnetic field to compensate for the electron energy losses, a tapered undulator. Note that LCLS routinely uses the tapered undulators not only to compensate for the energy loss of electrons due to the incoherent radiation in the undulator, but to double its output power to about 70 GW using its available tapering range of order of 0.8%.

Application of the KLM method for the upgrade LCLS-II was recently studied in [28]. The LCLS-II undulators will have variable gaps and in principle are tunable in a wide range of values of the undulator parameter K. It is important that quasi-monochromatic radiation produced with self-seeding allows a much better control of the trapping and deceleration of the electrons in the electromagnetic field of the radiation. The simulation studies suggest that it is feasible, with LCLS-like electron beam parameters, to generate coherent, TW-level, hard x-ray pulses within a $\sim$ 200m long, tapered undulator system. Together with output at the fundamental resonant wavelength, there will also be strong 3rd harmonic emission ($P_3 \geq 100$ GW) for planar-polarized undulators. To further improve the performance and shorten the undulator length, one can adopt a helical undulator for the FEL.

NOISE SUPPRESSION IN SEEDING

In free electron lasers, shot noise provides the startup radiation for Self-Amplified Spontaneous Emission (SASE), but also drives hazardous instabilities that might impede coherent processes. For example, the microbunching instability incapacitates diagnostics of the beam and can lead to degradation of the FEL performance [29–34]. In seeded FELs shot noise competes with external modulations of the beam being amplified in the process of the seeding [29, 35, 36]. Suppressing shot noise could have numerous accelerator applications, including controlling instabilities, reducing laser power requirements for seeding FELs, and increasing efficiency in cooling relativistic beams [37, 38].

Suppression of long wavelength shot noise was observed in microwave tubes as early as the 1950s, [39], and more recently similar effects (though from different physics) have emerged in semiconductor devices [40]. In the last few years, several groups have independently proposed suppressing shot noise at short wavelengths in relativistic electron beams [38, 41–43].

The quantify that defines the density fluctuations at a wave vector k is

$$F(k) \equiv \frac{1}{N}\sum_{j,l} e^{ik(z_j - z_l)}\,, \tag{2}$$

where the sum is over all N electrons in the beam and z_j is the longitudinal position along the bunch of the jth electron. If the positions of electrons in the bunch are uncorrelated (shot noise), the $N(N-1)$ random phases in (2) corresponding to $j \neq l$ cancel each other, and we find the expected noise factor is $F(k) = 1$. If instead the electrons are grouped into microbunches spaced by λ (e.g. in an FEL at saturation), then all $N(N-1)$ terms add in phase and the noise factor reaches a maximum value of $F(k) \approx N$. One can also arrange correlations between the particles in such a way that $F(k) < 1$. We refer to the last case as the *noise suppression*.

Correlations between the particle positions in the beam that can lead to the noise suppression arise from the particle interactions followed by their longitudinal motion along z. Due to the relativistic nature of the beam, the longitudinal velocity is very close to the speed of light, and the relative displacements of the particles in free motion is typically too small. A setup in which the noise suppression can occur was considered in [43]: it consists of an interaction region of length L_a, where space charge forces change particle energies, followed by a magnetic chicane characterized by the dispersive strength R_{56} which shifts the longitudinal particle positions. In a simplified model of [43] it was assumed that the particles are longitudinally frozen in the

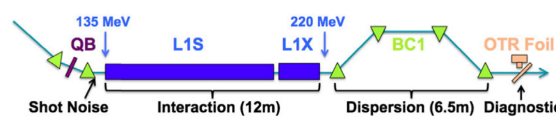

Figure 3: Schematic of the LCLS beam line used in the experiment for shot noise suppression, including the QB quadrupole, L1S and L1X accelerator sections, and bunch compressor chicane BC1. Radiation from the OTR foil served as the diagnostic.

interaction region, and there is negligible energy change through the dispersive region (i.e. the velocity bunching is small compared to the effect of the chicane strength). It was shown that in this case, for a beam with uniform density in the transverse cross section, the noise factor at the exit from the chicane can be written as

$$F(k) \approx (1 - \Upsilon)^2\,, \tag{3}$$

where

$$\Upsilon \equiv n_0 R_{56} A \text{ and } A \equiv \frac{4\pi r_e L_a}{S\gamma}\,, \tag{4}$$

with n_0 the longitudinal particles density (number of particle per unit length), r_e the classical electron radius, γ the relativistic factor, and S the transverse beam area. By

ISBN 978-3-95450-125-0

choosing R_{56} to set $\Upsilon_{1D} = 1$, we find that the minimal value of $F_{1D}(k)$ is zero. For a transverse Gaussian distribution of rms size σ, the transversely integrated noise factor has the form $F(k) = 1 - 2\Upsilon + \frac{4}{3}\Upsilon_G^2$, where in Eq. 4 one has to replace a by 2σ. For the Gaussian case, optimal shot noise suppression occurs at $\Upsilon = 3/4$, giving $F(k) = 1/4$.

Paper [44] presented the first experimental evidence of shot noise suppression in relativistic electrons. Using the scheme of Ref. [43] it was demonstrated that matching the beam's collective space charge forces to dispersion experienced by the particles in a subsequent magnetic system reduces broad-bandwidth shot noise current fluctuations as observed through a reduction in Optical Transition Radiation (OTR) of the beam.

For an experimental demonstration of shot noise suppression the first linac and bunch compressor sections of the Linac Coherent Light Source (LCLS) was used. The experiment included four components shown in Fig. 3: an initial shot noise distribution system consysting of two dipole magnets and the "QB" quadrupole which reset the beam to an initial shot noise distribution, an interaction region which includes the S-band (L1S) and X-band (L1X) accelerator sections, a dispersive region (magnetic chicane BC1), and a diagnostic station. Table 2 gives main beam and accelerator parameters.

Table 2: Parameter list for experimental conditions.

Beam energy	135-220 MeV
Beam charge	5-20 pC
Norm. Emittance (x,y)	0.2 μm
BC1 Dispersion (R_{56})	0.1-2.5 mm
QB strength	10.3 kG
Interact. Beam Size (σ_{Int})	30-200 μm
OTR Beam Size (σ_{OTR})	25 μm
Camera Bandwidth (λ)	400-750 nm
Camera Aperture (θ_{cam})	75 mrad

OTR emitted by the beam from a 1 μm thick aluminum foil inserted into the beam following BC1 was measured and compared with simulations and the analytical model. Fig. 4 shows that both simulations and the analytical model agree reasonably well with experimental results. The OTR intensity was suppressed by as much as 35% of the shot noise level.

SUMMARY

In this paper we reviewed several approaches, currently pursued at SLAC, to one of the main challenges for modern x-ray free electron lasers—an essential improvement of the temporal coherence of their output radiation. For soft x-ray FELs, seeding with an external laser, via harmonic multiplication, looks as a promising candidate. During the last 3 years extensive research work at SLAC, both theoretical and experimental, has been carried out to demonstrate the capabilities of the EEHG method.

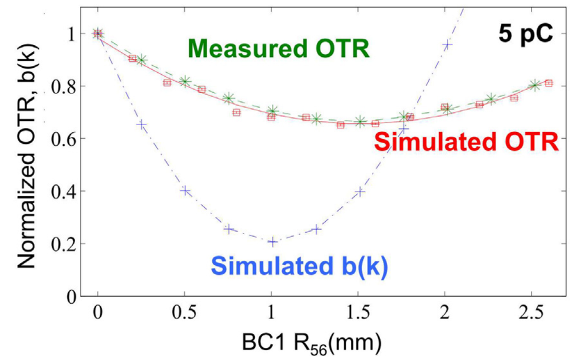

Figure 4: Simulation results compared to the experimental data for the bunch charge of 5 pC. The simulation predicts slightly stronger OTR suppression, perhaps due to the absence of transverse damping in the code. The shift in R_{56} in the OTR minimum is likely due to higher electron density in the experiment.

Hard x-ray self-seeding based on usage of Bragg forward reflection, was recently successfully demonstrated at LCLS. It opens a new road toward FELs with the output power on the terawatt scale.

The noise suppression technique, previously known for RF frequencies, has been experimentally achieved in the optical frequency range using a relativistic beam with typical for the FEL parameters.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy contract DE–AC02–76SF00515.

REFERENCES

[1] A. Kondratenko and E. Saldin, Particle Accelerators **10**, 207 (1980).

[2] R. Bonifacio, C. Pellegrini, and L. M. Narducci, Optics Communications **50**, 373 (1984).

[3] P. Emma, A. Akre, J. Arthur, R. Bionta, C. Bostedt, J. Bozek, A. Brachmann, P. Bucksbaum, R. Coffee, F.-J. Decker, *et al.*, Nat. Photonics **4**, 641 (2010).

[4] L. Young, E. P. Kanter, B. Krössig, Y. Li, A. M. March, S. T. Pratt, R. Santra, S. H. Southworth, N. Rohringer, L. F. DiMauro, *et al.*, Nature **466**, 56 (2010).

[5] H. N. Chapman, P. Fromme, A. Barty, T. A. White, R. A. Kirian, A. Aquila, M. S. Hunter, J. Schulz, D. P. DePonte, U. Weierstall, *et al.*, Nature **470**, 73 (2011).

[6] M. M. Seibert, T. Ekeberg, F. R. N. C. Maia, M. Svenda, J. Andreasson, O. Jonsson, D. Odic, B. Iwan, A. Rocker, D. Westphal, *et al.*, Nature **470**, 78 (2011).

[7] J. Feldhaus, E. Saldin, E. Schneidmiller, and M. Yurkov, Opt. Commun. **140**, 341 (1997).

[8] G. Lambert, T. Hara, D. Garzella, T. Tanikawa, M. Labat, B. Carre, H. Kitamura, T. Shintake, M. Bougeard, S. Inoue, *et al.*, Nature Physics **4**, 296 (2008).

ISBN 978-3-95450-125-0

[9] T. Togashi, E. J. Takahashi, K. Midorikawa, M. Aoyama, K. Yamakawa, T. Sato, A. Iwasaki, S. Owada, T. Okino, K. Yamanouchi, *et al.*, Opt. Express **19**(1), 317 (Jan 2011).

[10] L. Yu, Phys. Rev. A **44**, 5178 (1991).

[11] L.-H. Yu, M. Babzien, I. Ben-Zvi, L. F. DiMauro, A. Doyuran, W. Graves, E. Johnson, S. Krinsky, R. Malone, I. Pogorelsky, *et al.*, Science **289**(5481), 932 (2000).

[12] G. Stupakov, Phys. Rev. Lett. **102**, 074801 (2009).

[13] D. Xiang and G. Stupakov, Phys. Rev. ST Accel. Beams **12**, 030702 (2009).

[14] D. Xiang, E. Colby, M. Dunning, S. Gilevich, C. Hast, K. Jobe, D. McCormick, J. Nelson, T. O. Raubenheimer, K. Soong, *et al.*, Phys. Rev. Lett. **105**(11), 114801 (Sep 2010).

[15] D. Xiang and G. Stupakov, in *Proceedings of the 2009 Particle Accelerator Conference*, Vancouver, Canada (2009), p. 2327.

[16] E. Allaria, D. Xiang, and G. D. Ninno, in *Proceedings of the 2009 FEL Conference*, Liverpool, UK (2009), p. 39.

[17] S. Reiche, R. Abela, H.-H. Braun, B. Patterson, and M. Pedrozzi, in *Proceedings of the 2009 FEL Conference*, Liverpool, UK (2009), p. 51.

[18] K. Hacker, S. Khanv, G. A. Hamberg, V. Ziemann, A. Azima, P. Salen, and P. van der Meulen, in *Proceedings of the 2011 FEL Conference*, Shanghai, China (2011), p. 279.

[19] Z. T. Zhao, D. Wang, J. H. Chen, Z. H. Chen, H. X. Deng, J. G. Ding, C. Feng, Q. Gu, M. M. Huang, T. H. Lan, *et al.*, Nature Photonics **6**, 360 (2012).

[20] D. Xiang, E. Colby, M. Dunning, S. Gilevich, C. Hast, K. Jobe, D. McCormick, J. Nelson, T. O. Raubenheimer, K. Soong, *et al.*, Phys. Rev. Lett. **108**(2), 024802 (2012).

[21] E. Saldin, E. Schneidmiller, and M. Yurkov, Nucl. Instrum. Methods Phys. Res., Sect. A **475**, 86 (2001).

[22] Y. Ding, Z. Huang, and R. D. Ruth, Phys. Rev. ST Accel. Beams **13**, 060703 (2010).

[23] G. Geloni, V. Kochryan, and E. Saldin, Report 10-033, DESY (2010).

[24] G. Geloni, V. Kochryan, and E. Saldin, *Cost-effective way to enhance the capabilities of the LCLS beamline*, Report 10-133, DESY (2010).

[25] R. R. Lindberg and Y. V. Shvyd'ko, Phys. Rev. ST Accel. Beams **15**, 050706 (May 2012).

[26] J. Amann, W. Berg, V. Blank, F.-J. Decker, Y. Ding, P. Emma, Y. Feng, J. Frisch, D. Fritz, J. Hastings, *et al.*, Nature Photonics (2012), http://dx.doi.org/10.1038/nphoton.2012.180.

[27] N. Kroll, P. Morton, and M. Rosenbluth, IEEE J. Quantum Electron. **QE-17**, 1436 (1981).

[28] W. Fawley, J. Frisch, Z. Huang, Y. Jiao, H.-D. Nuhn, C. Pellegrini, S. Reiche, and J. Wu, in *Proceedings of the 2011 FEL Conference*, Shanghai, China (2011), p. 160.

[29] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Optics Communications **202**, 169 (2002).

[30] Z. Huang and K.-J. Kim, Phys. Rev. ST Accel. Beams **5**, 074401 (2002).

[31] R. Akre, D. Dowell, P. Emma, J. Frisch, S. Gilevich, G. Hays, P. Hering, R. Iverson, C. Limborg-Deprey, H. Loos, *et al.*, Phys. Rev. ST Accel. Beams **11**, 030703 (2008).

[32] M. Borland, Y. Chae, P. Emma, J. Lewellen, V. Bharadwaj, W. Fawley, P. Krejcik, C. Limborg, S. Milton, H.-D. Nuhn, *et al.*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **483**, 268 (2002).

[33] S. Heifets, G. Stupakov, and S. Krinsky, Phys. Rev. ST Accel. Beams **5**, 064401 (2002).

[34] A. Marinelli and J. B. Rosenzweig, Phys. Rev. ST Accel. Beams **13**, 110703 (2010).

[35] G. Stupakov, in *Proceedings of the 2010 FEL Conference*, Malmö City, Sweden (2010), p. 274.

[36] G. Stupakov, Z. Huang, and D. Ratner, in *Proceedings of the 2010 FEL Conference*, Malmö City, Sweden (2010), p. 278.

[37] A. A. Mikhailichenko and M. S. Zolotorev, Phys. Rev. Lett. **71**, 4146 (1993).

[38] V. N. Litvinenko, in *Proceedings of the 2009 FEL Conference*, Liverpool, UK (2009), p. 229.

[39] C. C. Cutler and C. F. Quate, Phys. Rev. **80**, 875 (1950).

[40] C. W. J. Beenakker and M. Büttiker, Phys. Rev. B **46**, 1889 (1992).

[41] A. Gover and E. Dyunin, Phys. Rev. Lett. **102**, 154801 (2009).

[42] A. Nause, E. Dyunin, and A. Gover, Journal of Applied Physics **107**(10), 103101 (2010).

[43] D. Ratner, Z. Huang, and G. Stupakov, Phys. Rev. ST Accel. Beams **14**, 060710 (2011).

[44] D. Ratner and G. Stupakov, Phys. Rev. Lett. **109**, 034801 (Jul 2012).

ISBN 978-3-95450-125-0