SIMULATION OF A MANY PERIOD DIELECTRIC GRATING-BASED ELECTRON ACCELERATOR

W. Kuropka[1]*, R. Assmann, U.Dorda, F. Mayet[1], DESY Hamburg, Germany
[1]also at University of Hamburg, Germany

Abstract

Dielectric laser driven particle accelerators have become a research area of major interest due to the high acceleration gradients achievable. Those are mainly attributed to the high damage thresholds of dielectrics at optical frequencies. Simulations of these structures are usually computed with Particle-In-Cell (PIC) codes. Their accuracy and self consistency comes with a major drawback of high computation costs. Computation of structures consistent of hundreds to thousands of periods are only viable with High Performance Computing clusters.

In this proceeding a compromise of CST [1] PIC simulations combined with a transfer function model is presented to simulate relativistic electron accelerators for particle energies up to the GeV regime or higher. In addition a simplified example accelerator design is investigated and the required electron bunch parameters from a sub-relativistic source are computed.

DIELECTRIC LASER-DRIVEN GRATING

Several different structure designs for laser driven dielectric accelerators have been proposed [2]. In this work we focus on a transversely illuminated pillar structure with rectangular shape (see Fig. 1). The grating-like pillars form diffraction mode fields in the particle channel. These fields can be described using spatial harmonics along the channel [3]. If the grating is illuminated from both sides with a linearly polarized phase synchronous laser, the accelerating fields are nearly independent of the transverse position in the channel. In the direction along the grating grooves only a magnetic field is present, which leads to no transverse forces on charged particles in this dimension.

If the grating period matches the incident laser wavelength, the first spatial harmonic exhibits speed of light phase velocity. This harmonic will be used here to accelerate electrons, which are already at relativistic energies, thus traveling almost with speed of light velocity. If electrons are injected at a phase relative to the laser field where they are accelerated, they stay synchronous with this first spatial harmonic. For electrons with lower energies the grating period might be shortened to achieve lower phase velocities or even use higher order spatial harmonics.

In these proceedings we focus on relativistic particles, since the SINBAD facility at DESY will be used for later experiments [4].

* willi.kuropka@desy.de

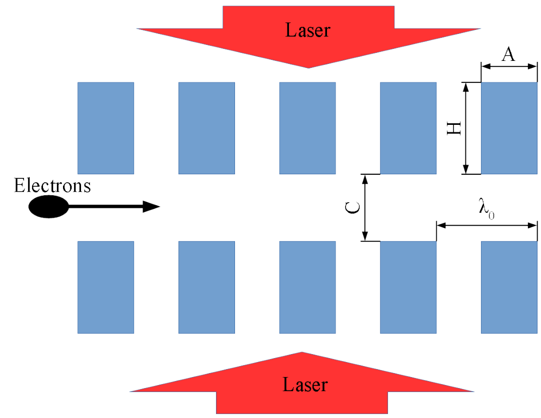

Figure 1: Schematic of the grating structure. The parameters $A = 0.5 \cdot \lambda_0$, $C = 0.37 \cdot \lambda_0$ and $H = 0.87 \cdot \lambda_0$ for silicon with a relative permittivity of $\epsilon_r = 11.9$.

SIMULATION

Method

The results of a single period EM simulation with CST were used to perform particle tracking parameter sweeps at different particle energies, transverse positions over the channel and entry angles. The transverse positions, angles and energies after one grating period dependent on the electron to laser phase were retrieved from the simulation. From this data a multivariate polynomial model was derived [5]. With this model transfer functions can be used to track a particle from one period to the next. The electron to laser phase slippage is calculated analytically from the particle energy, assuming the energy gain per period is small compared to the particle energy and that the angles of the particles to the accelerators longitudinal axis are small. Space charge and other collective effects are neglected for now due to the relativistic particle energies and low charges aimed at in DLA experiments.

To check the model a comparison with a 3D tracking simulation for a few grating periods was carried out. Mid range numbers of periods were also checked against a linear interpolation representation of the data. Theses comparisons show good agreement with the polynomial model.

Performance

The proposed method shortcuts the calculation of the fields of every grating period. Due to the periodicity of the structure the field calculation can be carried out for a single grating period. A parameter sweep can be done with a tracking code with the pre-calculated EM fields. Linearization

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and fitting via linear regression is fast. The linear interpolation scheme has a higher computation cost and was only used to verify the polynomial fitting in addition to the standard cross correlation schemes. A drawback of the method is that changes in the structure design make a new PIC parameter sweep and fitting run necessary.

The calculation of the particle data with the polynomial model in 5th order takes only fractions of the resources of a PIC code. There the whole structure with all its periods had to be modeled in the simulation domain. Due to the size of the necessary simulation domain a calculation using a closed model in a PIC code is not practical. But a simulation period by period transferring the particle parameters is feasible.

On a system with an Intel Core i7-6700 @ 3.4 GHz the 3D particle tracking with CST and the pre-calculated EM fields has an overall computation time for one period with one particle of 19 s using all cores. The polynomial model has a computation time of 0.37 ms for a single core. Since in the 3D tracking multiple particles can be added in one calculation the overall computation time for one bunch strongly depends on the longitudinal discretization of the bunch. The polynomial model is continuous and only depends on the number of particles and periods.

ACCELERATOR DESIGN

The DLA structure was optimized for a maximum acceleration gradient. A parameter sweep with a EM solver was performed for one grating period. From the results the amplitudes of the spatial harmonics were calculated via Fourier transform. Geometry values which result in a high amplitude of the first spatial harmonic were chosen, since the design particle is almost in phase with this mode. The results are in good agreement with previous work [6].

The design was chosen to have no additional external focusing. A ponderomotive, RF-focusing like effect caused by the higher order spatial harmonics makes stable trajectories in the plane of the grating possible [7]. The parameters shown in Fig. 1 influence the amplitudes and phases of the spatial harmonics. Here a design was chosen that overlaps transverse focusing and accelerating fields at the same electron to laser phases (see Fig. 2). Since the diffracted fields assert no forces on particles in the other transverse plain, after a number of periods the grating is rotated orthogonally around the longitudinal axis to achieve focusing in both transverse directions (see Fig. 3).

Even with relativistic particles the phase slippage has to be considered, if the simulated device is hundred thousands of periods long. For a reference design particle with no angle or transverse offset several field free drift sections were introduced to correct the electron to laser phase. This is necessary to keep the particles in a focusing and accelerating phase as described in Fig. 2. A starting energy of $E_0 = 100$ MeV was chosen to limit the phase slippage to reasonable values. An uncorrelated relative energy spread of $\frac{\Delta E}{E} = 3.46\,\%$ is assumed, which is conservative w.r.t the achievable parameter range of modern conventional accelerators [8]. The beam emittance will be derived from the simulation. The target energy will be $E_\mathrm{f} = 1$ GeV.

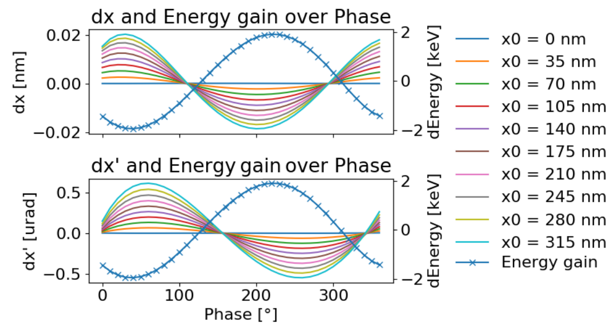

Figure 2: Electron to laser phase scan from the polynomial model for one grating period. The plots show the position and angle offset (or kick) for different transverse starting positions for $x'_0 = 0$ rad and $E_0 = 100$ MeV. The second axis shows the energy gain dependent on this phase. In the range from 200° to 300° an initial positive position offset has a negative angle offset, negative position offset and energy gain.

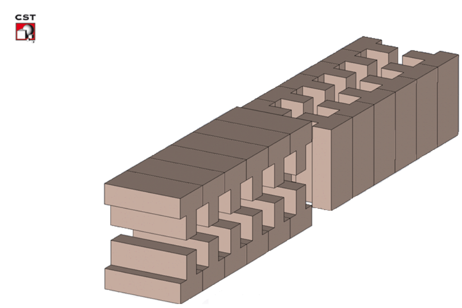

Figure 3: Schematic of the rotated grating stages. In the simulation one stage consists of 100 periods.

The laser wavelength is chosen to be 2 µm and so is the grating period to accelerate in the first spatial harmonic. The height of the stages is set to be 5 µm. The illumination over the DLA stages is assumed to be distributed evenly in longitudinal and transverse direction. A laser spot size was considered with a slight pulse front tilt resulting in 5 µm x 25 µm. Here other technical issues are not further addressed, i.e. the details of the laser pulse distribution to the gratings.

Laser pulse energy requirements for the stages are estimated from the field amplitudes of the EM simulation. For all the acceleration stages a few tens of mJs are sufficient. Laser distribution will have significant losses in the range of 90 % or higher, which would make a laser source in the hundreds of mJ to single digit joule range necessary.

SIMULATION RESULTS

The grating was illuminated with a laser field amplitude of $\widehat{E}_\mathrm{laser} = 2\,\mathrm{GV\,m^{-1}}$ with an efficiency into the first spatial harmonic of $\eta = \widehat{E}_\mathrm{1SH}/\widehat{E}_\mathrm{laser} = 0.5$. After

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550 000 periods the design particle reaches an energy of 1.041 GeV. This corresponds to a mean acceleration gradient of $G_{\mathrm{acc}} = 946\,\mathrm{MeV\,m^{-1}}$ and a length of the setup of 1.1 m.

Sweeping over the available parameter space for the initial particle angles, positions, energies and phases yields a maximum available transverse and longitudinal phase space. From there a viable normally distributed electron bunch was estimated. The phase spaces and emittance of the ASTRA [9] generated electron bunch are shown in Fig. 4. A central electron to laser phase was chosen to be $\phi_0 = 180°$. For this configuration there is significant charge loss due to the collimation of the beam by the accelerator (see Fig. 5) and thus a smaller final emittance.

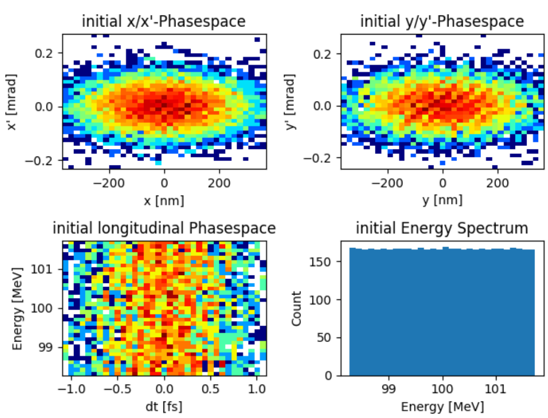

Figure 4: Phase spaces and spectrum of the initial electron bunch before the DLA. The normalized transverse emittance at 100 MeV is $\epsilon_{\mathrm{trN}} = 10\,\mathrm{\mu m\,mrad}$. The uniform energy spread is $\frac{\Delta E}{E} = 3.46\,\%$. The bunch charge is $Q = 0.8\,\mathrm{fC}$ and the rms bunch length is $\sigma_{\mathrm{t}} = 0.5\,\mathrm{fs}$. The transverse rms beam size is $\sigma_{\mathrm{x,y}} = 162\,\mathrm{nm}$.

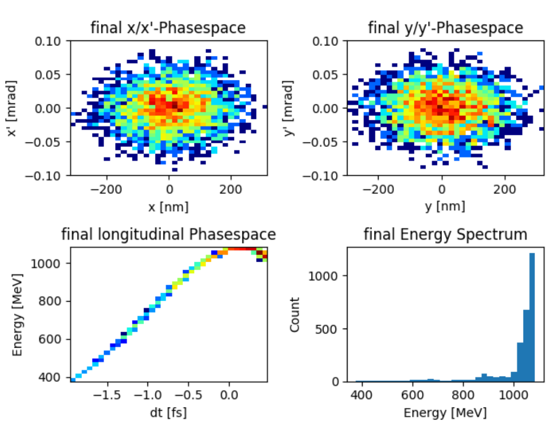

Figure 5: Phase spaces and spectrum of the final electron bunch after the DLA. The normalized transverse emittance at 1.012 GeV is $\epsilon_{\mathrm{trN}} = 3.5\,\mathrm{\mu m\,mrad}$. The rms energy spread is $\sigma_{\Delta E} = 119\,\mathrm{MeV}$.The final bunch charge is $Q = 0.45\,\mathrm{fC}$ and the rms bunch length is $\sigma_{\mathrm{t}} = 0.47\,\mathrm{fs}$. The transverse rms beam size is $\sigma_{\mathrm{x,y}} = 104\,\mathrm{nm}$.

In Fig. 6 the fraction of the initial bunch that passed the whole accelerator is shown with its parameters. Since collective effects are neglected, this can be an actual viable bunch. These would be the to be delivered parameters from a 100 MeV source, if no charge loss is desired. Noticeable is the emittance blow up from $\epsilon_{\mathrm{trN}} = 0.08\,\mathrm{\mu m\,mrad}$ to $3.5\,\mathrm{\mu m\,mrad}$ which is most likely due to the non-optimized drift sections introduced for electron to laser phase correction.

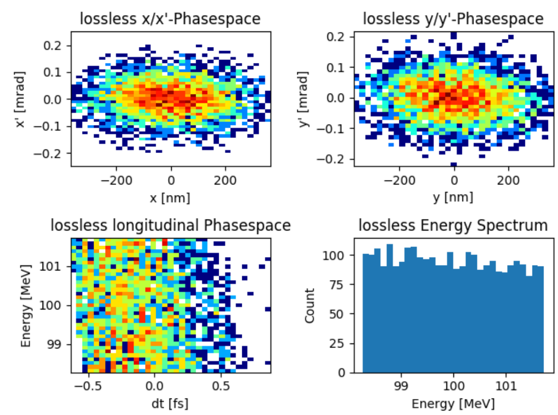

Figure 6: Phase spaces and spectrum of the passing fraction of the initial electron bunch before the DLA. The normalized transverse emittance at 100 MeV is $\epsilon_{\mathrm{trN}} = 0.08\,\mathrm{\mu m\,mrad}$. The uniform energy spread is $\frac{\Delta E}{E} = 3.46\,\%$. The bunch charge is $Q = 0.45\,\mathrm{fC}$ and the rms bunch length is $\sigma_{\mathrm{t}} = 0.29\,\mathrm{fs}$. The transverse rms beam size is $\sigma_{\mathrm{x,y}} = 146\,\mathrm{nm}$. These parameters would correspond to the output of a sub-relativistic source.

CONCLUSION AND OUTLOOK

It was shown that the presented method can be used to simulate grating-based DLAs with large numbers of periods efficiently. The example DLA design presented can be a starting point for the development of a more sophisticated, realistic model. Due to the strong simplification of the presented model more research is necessary to make a statement about feasibility of the accelerator design. The posed requirements on a sub-relativistic source are challenging. Nanotip sources in combination with different DLA designs are promising candidates to produce the low emittances and beam spot sizes necessary [10].

To improve the presented method more features will be added, i.e. simplecticity check, space charge and wake fields. At the moment the code is parallelized using MPI. An OpenCL version is planned to be implemented to take advantage of GPU computation resources.

ACKNOWLEDGMENTS

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REFERENCES

[1] CST - Computer Simulation Technology, www.cst.com

[2] R.J. England *et al.*, *Rev. Mod. Phys.*, vol. 86, pp. 1337-–1389, 2014.

[3] J. Plettner *et al.*, *J. Mod. Opt.*, vol. 58, no. 17, pp. 1518–1528, 2011.

[4] U. Dorda *et al.*, “The dedicated accelerator R&D facility SINBAD at DESY”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper MOPVA012.

[5] scikit-learn, www.scikit-learn.org

[6] Y. Wei *et al.*, “Investigations into dielectric laser-driven accelerators using the CST and VSim simulation code”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, paper WEPWA051, pp. 2618–2620.

[7] J. Rosenzweig and L. Serafini, *Phys. Rev. E*, vol. 49, pp. 1599–1602, 1994.

[8] F. Mayet *et al.*, “Simulations and plans for a dielectric laser acceleration experiment at SINBAD´´, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper WEPVA007.

[9] K. Floettmann, ASTRA - A space charge tracking algorithm, http://www.desy.de/~mpyflo/.

[10] J. McNeur *et al.*, *J. Phys. B*, vol. 49, p. 034006, 2016.

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