Using short Drive Laser Pulses to achieve net Focusing Forces in tailored Dual Grating Dielectric Structures.

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Introduction

- In simple β-matched grating structures due to the nature of the laser induced steady-state in-channel fields the per period forces on the particles are out of phase and hence at a maximum energy gain phase mostly in longitudinal direction
- Stable acceleration of realistic electron beams in a DLA channel requires the presence of significant net transverse forces with no, or at least accelerating longitudinal force
- **Here we simulate and study the effect of using the transient temporal shape of short Gaussian drive laser pulses in order to achieve suitable field configurations for potentially stable acceleration of relativistic electrons in the horizontal plane**

Per-Period Force (Analytical Description)

- The in-channel field can be described by the infinite sum of spatial harmonics
- n^{th} order force components (dual grating), via Lorentz-Force

$$F_x^{(n)}(x,y) = qc\sqrt{\frac{n^2}{\beta_m^2}-1}\cdot B_{z0}^{(n)}\cdot\sin(\Psi_m^{(n)}x+\tilde{\phi}_0^{(n)})\cdot\Delta_{m,+}^{(n)}(y),$$
$$F_y^{(n)}(x,y) = qc\left[\frac{n}{\beta_m}-\beta_p\right]\cdot B_{z0}^{(n)}\cdot\cos(\Psi_m^{(n)}x+\tilde{\phi}_0^{(n)})\cdot\Delta_{m,-}^{(n)}(y).$$

$$\Delta_{m,\pm}^{(n)}(y) = e^{-\delta_m^{(n)}y}\pm e^{-\delta_m^{(n)}(L_{gap}-y)}$$
$$\Psi_m^{(n)} = k_0\left(\frac{n}{\beta_m}-\frac{1}{\beta_p}\right)$$
$$\delta^{(n)} = k_0\sqrt{\frac{n^2}{\beta^2}-1}$$

β_m matched n. velocity
β_p actual n. velocity
L_{gap} channel gap width

- n^{th} order per-period force

$$\langle F_{x,y}\rangle^{(n)}(y) = \frac{1}{\lambda_x}\int_0^{\lambda_x} F_{x,y}^{(n)}(x,y)dx$$

- **The longitudinal and transverse force components are out of phase in the ideal steady state case! → Resonant defocusing**

Enhancement of the transverse Force Component using Transient Drive Laser Fields (Analytical Description)

- $\langle F_y\rangle$ can be enhanced by having a significant mismatch between β_m and β_p, for example by entering the structure with an angle in the x-z plane
- Or: Do not assume B_{z0} to be constant (i.e. steady state)!

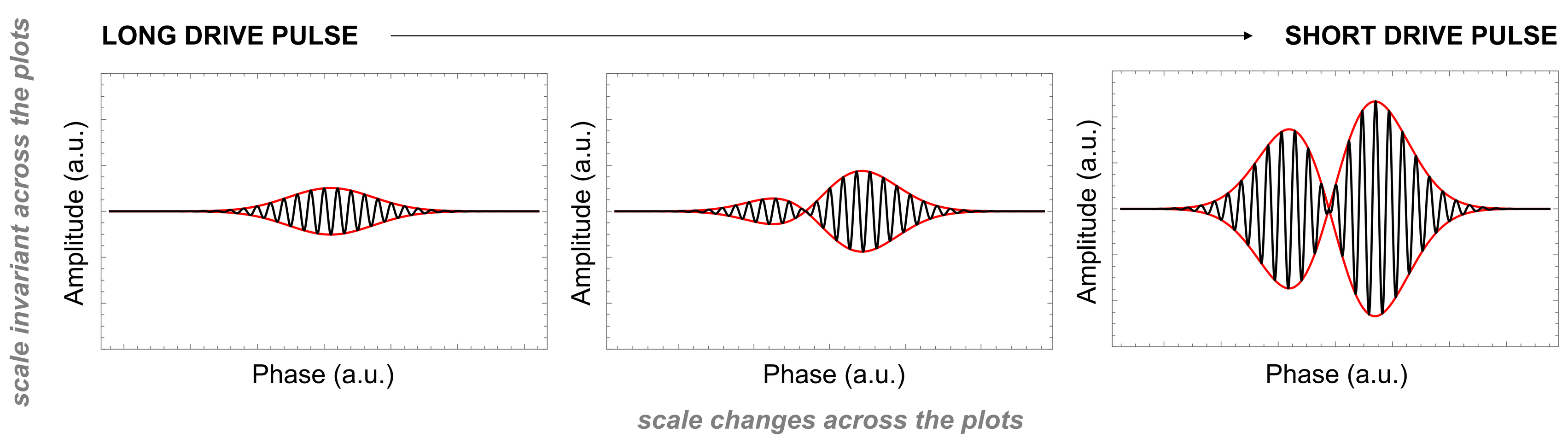
Assumptions:
No transverse motion during one period, slope of the B_{z0} (envelope) is linear over one period, phase is constant over one period, matched case

$$\langle F_y\rangle^{(n)}(y) \sim \int_0^{\lambda_x}(B_{z,0,0}^{(n)}+\mathrm{d}_x B_{z,0}^{(n)}\cdot x)\cdot\cos(\Psi_m^{(n)}x+\tilde{\phi}_0^{(n)})dx.$$

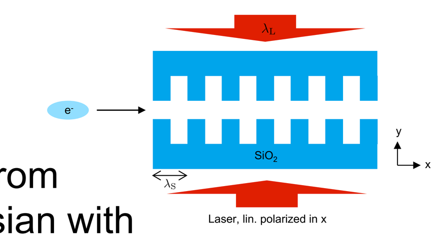
$$\Rightarrow \langle F_y\rangle^{(1)}(y) \sim \left(B_{z,0,0}^{(1)}+\frac{\mathrm{d}_x B_{z,0}^{(1)}}{2}\cdot\lambda_x\right)\cdot\cos(\tilde{\phi}_0^{(1)}).$$

- The first order per-period transverse force depends on both the amplitude **and its slope** (albeit multiplied with the drive laser wavelength)
- If the slope is significantly steep…
  …the transverse per-period force can be enhanced
  …the sign of the slope makes a difference!

Illustration



Numerical Simulations (VSim 7.2)

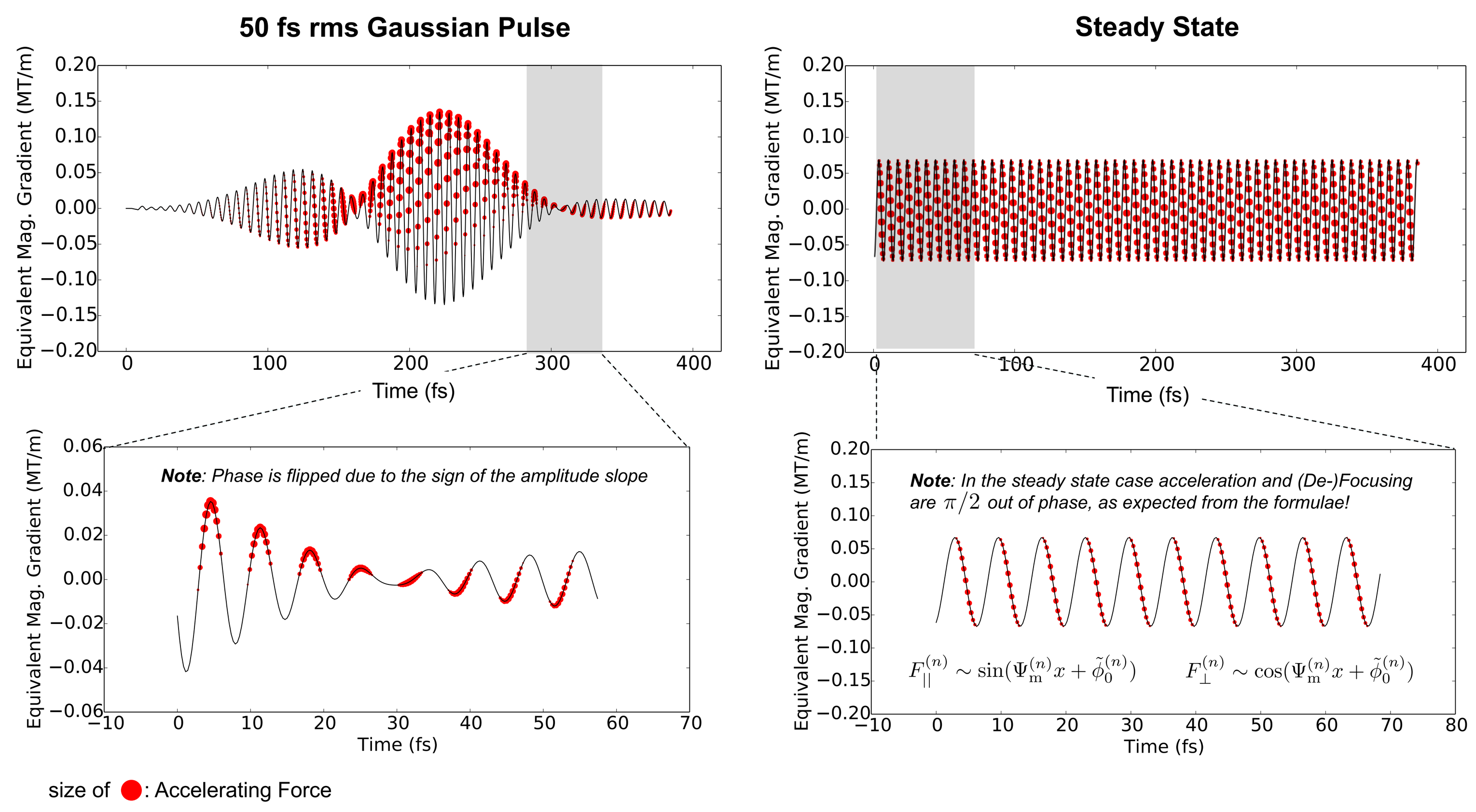


- **Goal**: Verification of the enhancement effect
- **Premise**: Dual grating (matched to 50 MeV) illuminated from both sides with a 50 fs rms phase-locked temporal Gaussian with max amplitude of 0.5 GV/m
- **Figure of merit**: Equivalent magnetic focusing gradient (K. Wootton, et al.)
- **Scheme**:

Calculate the transient field for one cell/period → Calculate the per-period average force on a single beta-matched particle → Calculate the equivalent magnetic focusing gradient → Repeat this for all phases along the Gaussian drive pulse

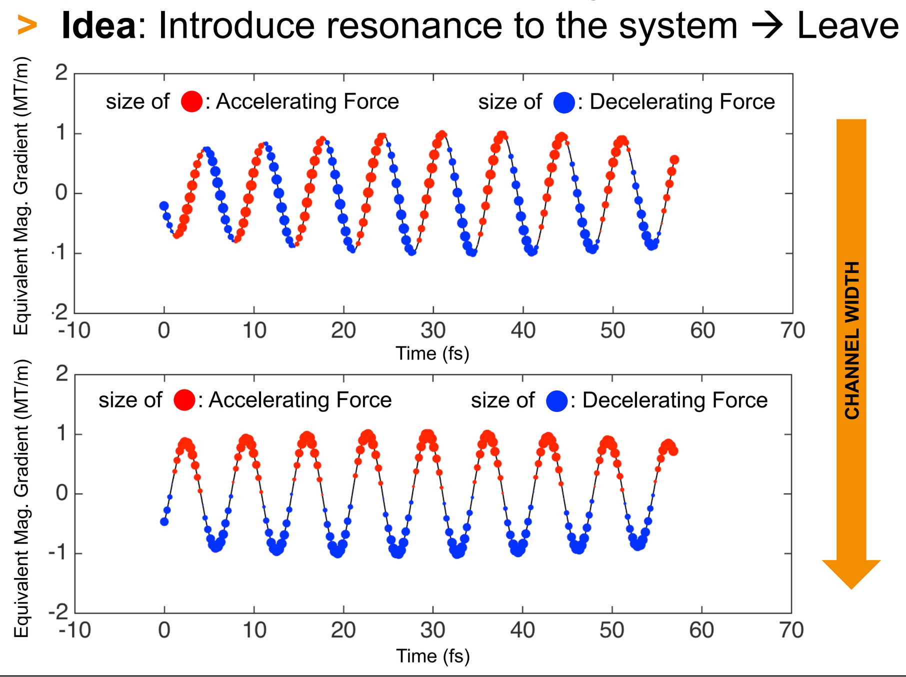
$$G = \frac{\partial_\perp\langle F_\perp\rangle_\lambda}{q_e c} \rightarrow \left[\frac{\mathrm{T}}{\mathrm{m}}\right]$$

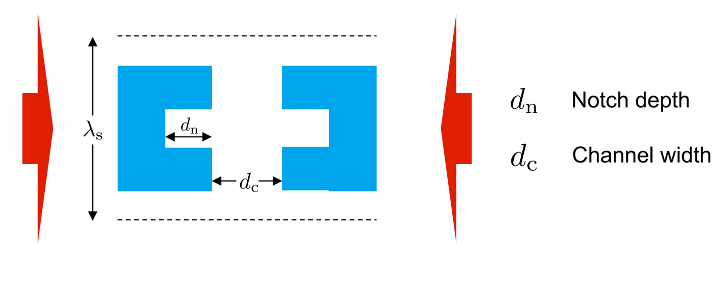
- **Results –** Comparison with steady state case (same max amplitude)



Optimization (VSim 7.2)

- **Question**: Is it possible – in addition to the enhancement – to alter the slope and also the phase relation between focusing and acceleration?
- **Idea**: Introduce resonance to the system → Leave the ideal picture

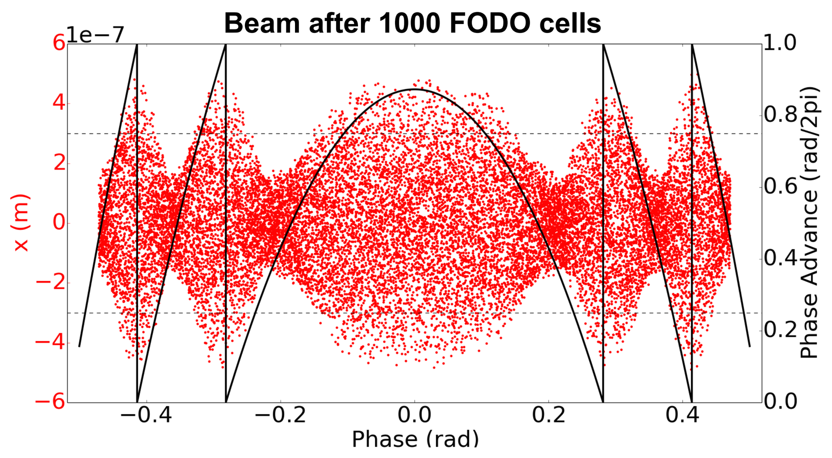




Acceleration and focusing can be brought in phase by altering the geometry!

Phase-Dependent Focusing – DLA Transport Line

- **Problem:** In DLA-based focusing systems the focusing strength depends on the laser to electron phase
- Along a phase range of π/2 the equivalent k value of a usual DLA can vary from 0 to ~10^6 → Strong effect on the phase advance of individual slices along the beam!
- **Study:** Classical transport matrix approach with phase dep. k value



- **DLA FODO line:** dB_{max} = 2.0 MT/m, 10 cells/element, 10 elements/drift, 50 MeV electrons, 1 fs uniform
- **Results:** After a long distance, the x-phi phase space is strongly disturbed!
- **Outlook**: What are the characteristic thresholds of a DLA-based transport line?

Conclusion

- **The transverse force can be enhanced by using transient fields with strong slopes**
- **The geometry of the grating can influence the phase relation between acceleration and (de-)focusing**
- First PIC simulations show slightly worse results compared to the simple field analysis, but more sophisticated structures could mitigate this
- More elaborate PIC simulations must show how nonlinearities in the fields affect the beam quality in multi-period structures!

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