Challenges in Simulating Beam Dynamics of Dielectric Laser Acceleration

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ACHIP

GORDON AND BETTY MOORE FOUNDATION

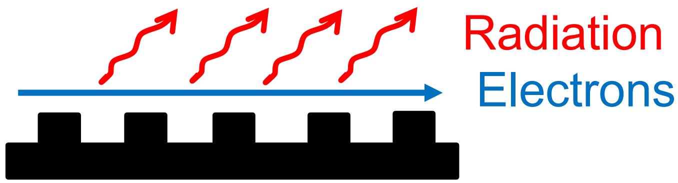
Bundesministerium für Bildung und Forschung

Contents

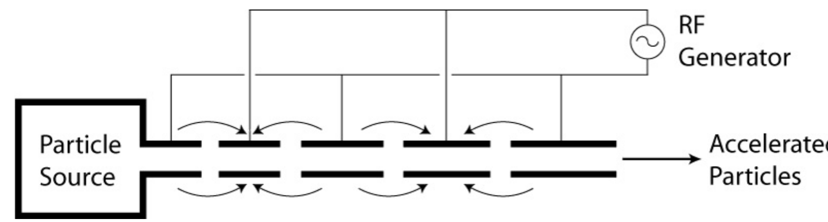
- Introduction to Dielectric Laser Acceleration (DLA)
  - Experimental demonstrations
  - The ACHIP collaboration
- Beam dynamics: tracking with *DLAtrack6D*
- Stabilization and scalability of DLA
- Current and future experiments

Dielectric Laser Acclerator (DLA) principle

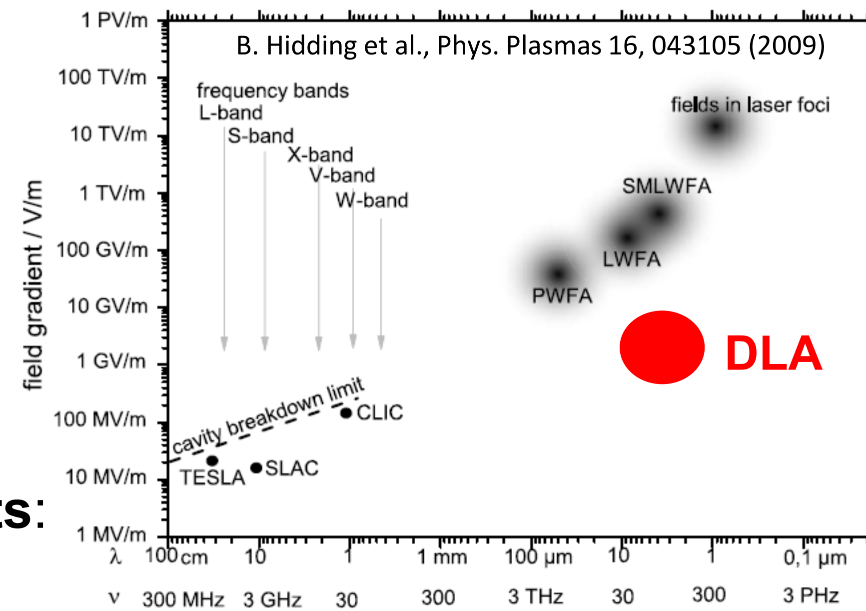
- Idea is quite old
  → **Inverse** effects
  - Smith-Purcell (grating radiation)
  - Cherenkov (electrons superluminal in material)



- Same principle as **Wideroe-Linac** (Non- resonant)

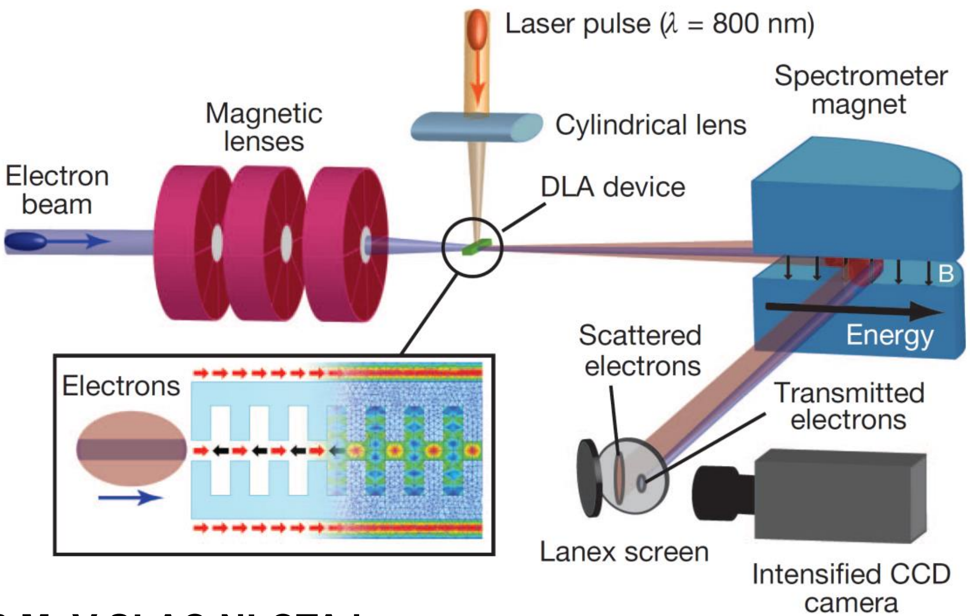


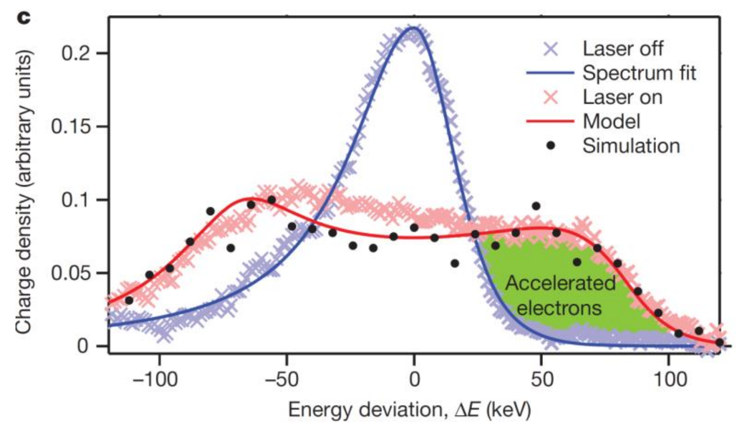
- **Dielectrics** can withstand fields up to **10GV/m**
- **Gradients larger than 1GeV/m** (limited by breakdown)

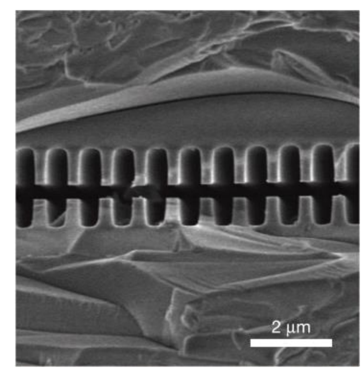


- Recent **technological improvements**: Laser pulses, micro-fabrication

Experiments with relativistic e-beams

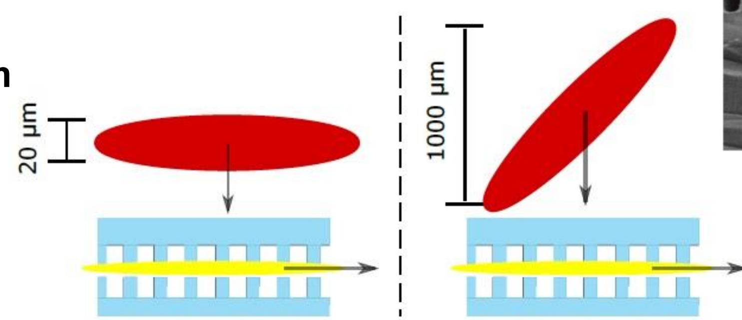






<u>60 MeV SLAC NLCTA beam:</u>
- E. Peralta et al. *Nature* 2013, ***300* MeV/m**

- K. Wooton et al.: increased to ***690* MeV/m** (*Optics Letters* 2016)



<u>6 MeV UCLA Pegasus beam:</u>
D. Cesar et al. *Nat Comm Phys*. 2018, ***850* MeV/m** with pulse front tilt

Accelerator on a Chip Intl. Program (ACHIP)
- funded by the Moore Foundation

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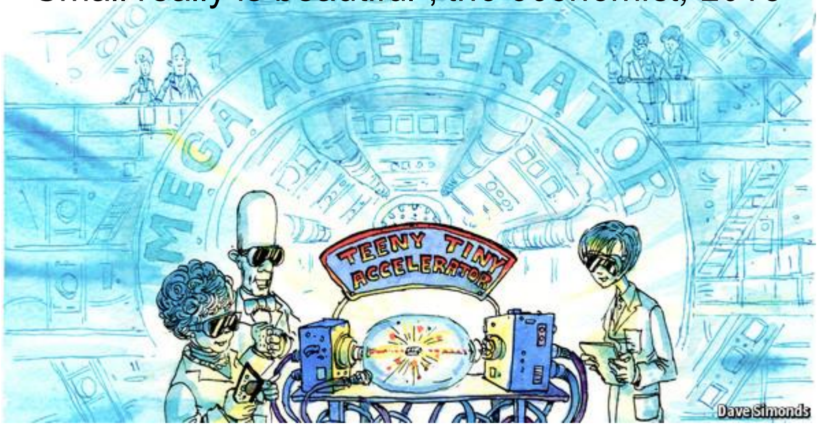
"Small really is beautiful", *the economist, 2013*



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"Make a chip that provide

Stanford University

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

TECH-X SIMULATIONS EMPOWERING YOUR INNOVATIONS

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UCLA

SLAC NATIONAL ACCELERATOR LABORATORY

PAUL SCHERRER INSTITUT PSI

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

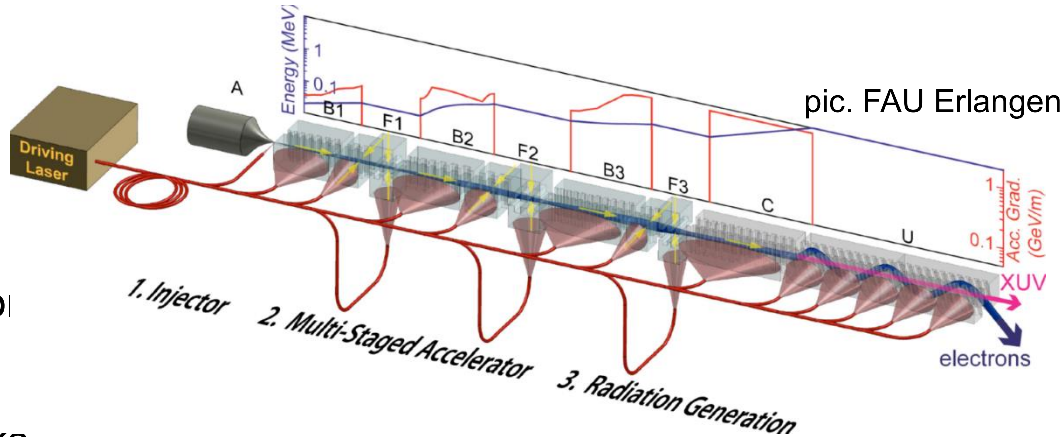
DESY

PURDUE UNIVERSITY

Working groups:

…to work towards our dream laser accelerator

- Injectors
  - Electron sources
  - Sub-relativistic DLA
- Relativistic Accleration
  - Large scale integration (Accelerato
- Lasers and Laser Coupling
  - On-chip laser delivery tree-networks
- **Simulations and Beam Dynamics**
  - **Beam dynamics schemes design**
  - **Large and small scale computation**
  - **Intensity effects**
- Radiation Generation and Applications
- Integration (fit everything in a shoe-box)



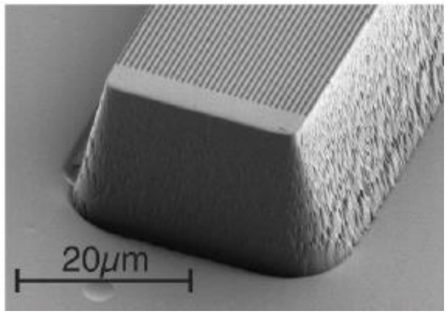
pic. FAU Erlangen

Goal #1:
60keV → 1MeV
on-chip accelerator

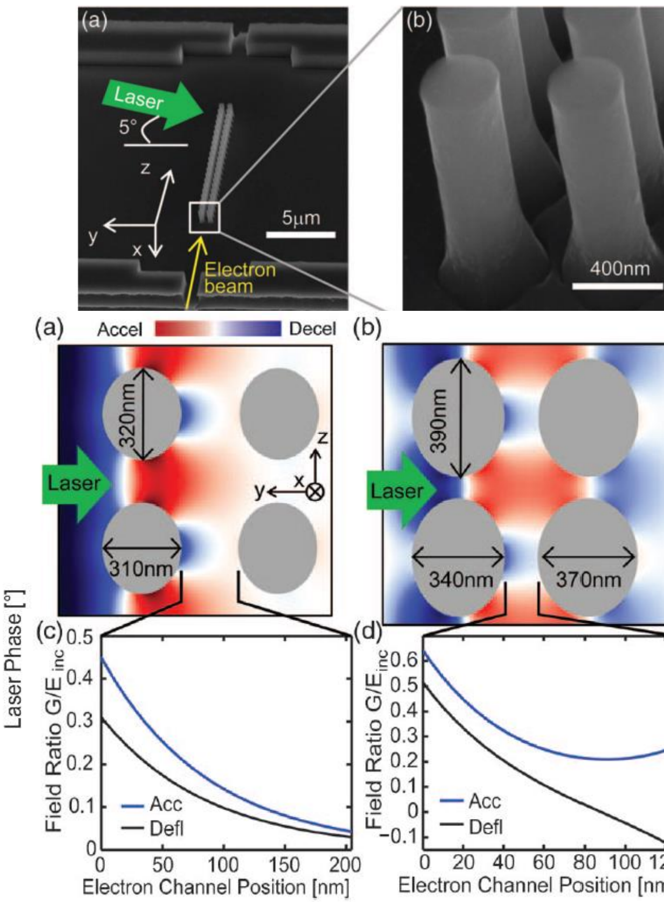
Sub-relativistic accelerators

FAU Erlangen:
28 keV electrons
(v/c=0.32)
25 MeV/m gradient
Single grating

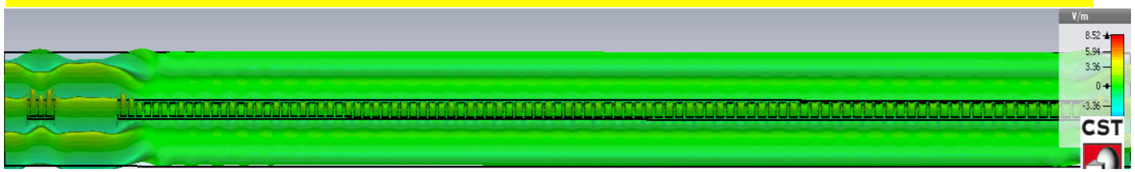
Breuer et. al.
PRL 2013

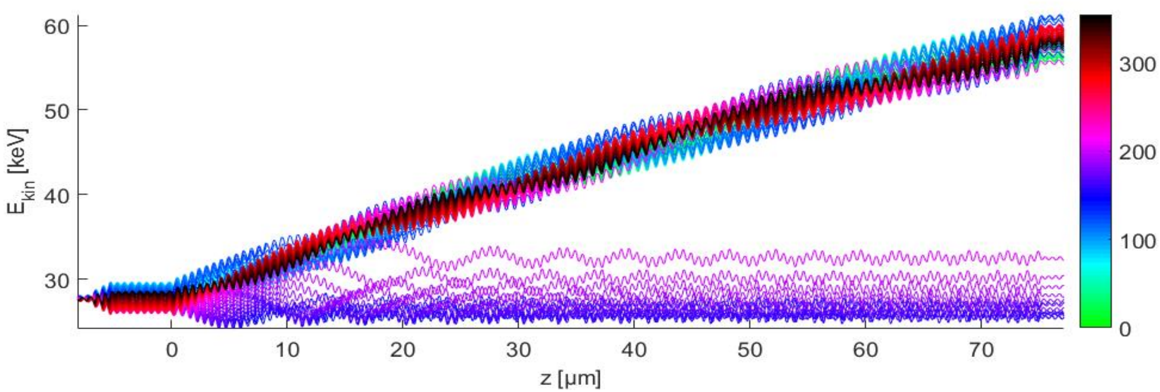


Stanford: 370MeV/m @ ~90keV
K.Leedle et al. Optics Letters, 2015



<u>Inherent problem</u>: **dephasing** due to velocity increase
<u>Solution</u>: **chirped grating**





U Niedermayer et al. J. Phys.: Conf. Ser. **874** 012041 (2017).

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Fields in a single DLA cell

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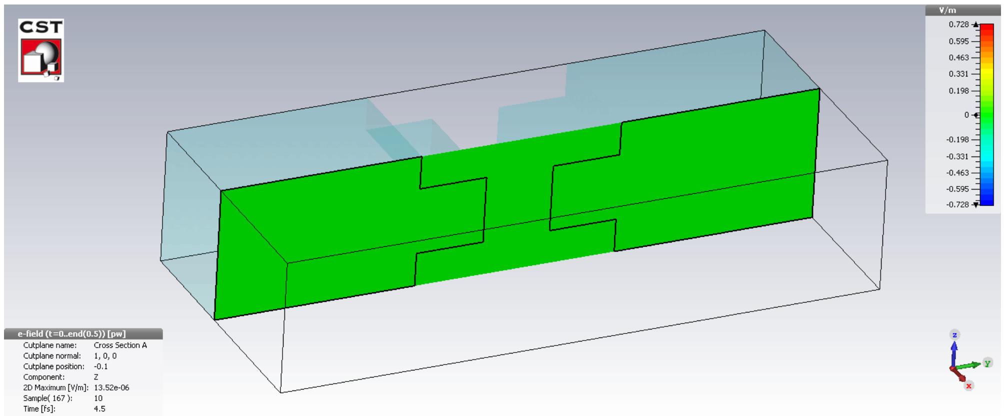


Simulation not very challenging
- FD / FI TD
- FD FD
- FE FD

$$\Delta W(x,y;s) = q \int_{-\lambda_g/2}^{\lambda_g/2} E_z(x,y,z;t=(z+s)/v)\mathrm{d}z$$

$$= q \int_{-\lambda_g/2}^{\lambda_g/2} \Re\{\underline{E}_z(x,y,z)e^{i\omega(z+s)/v}\}\mathrm{d}z$$

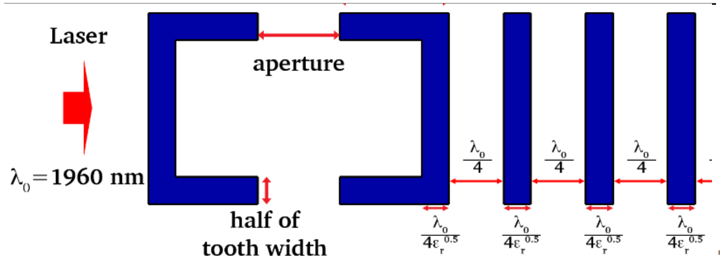
$$= q\lambda_g \Re\left\{e^{2\pi i \frac{s}{\beta\lambda_0}}\underline{e}_m(x,y)\right\}$$

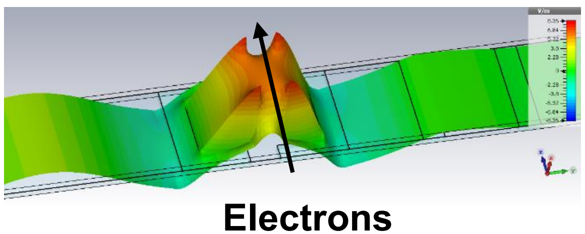
$$\lambda_g = m\beta\lambda_0$$

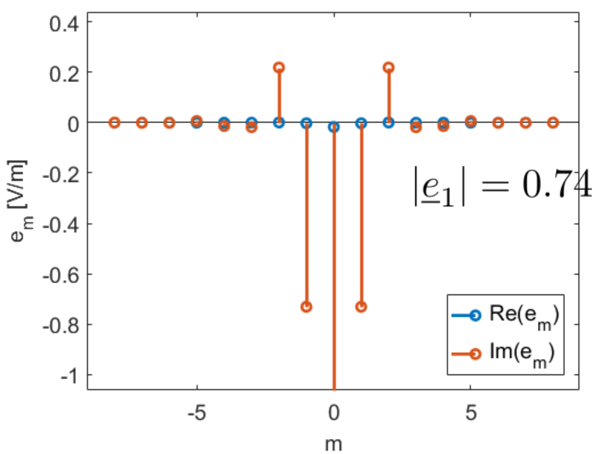
$$\underline{E}_z(x,y,z) = \sum_m \underline{e}_m e^{-im\frac{2\pi}{\lambda_g}z}$$

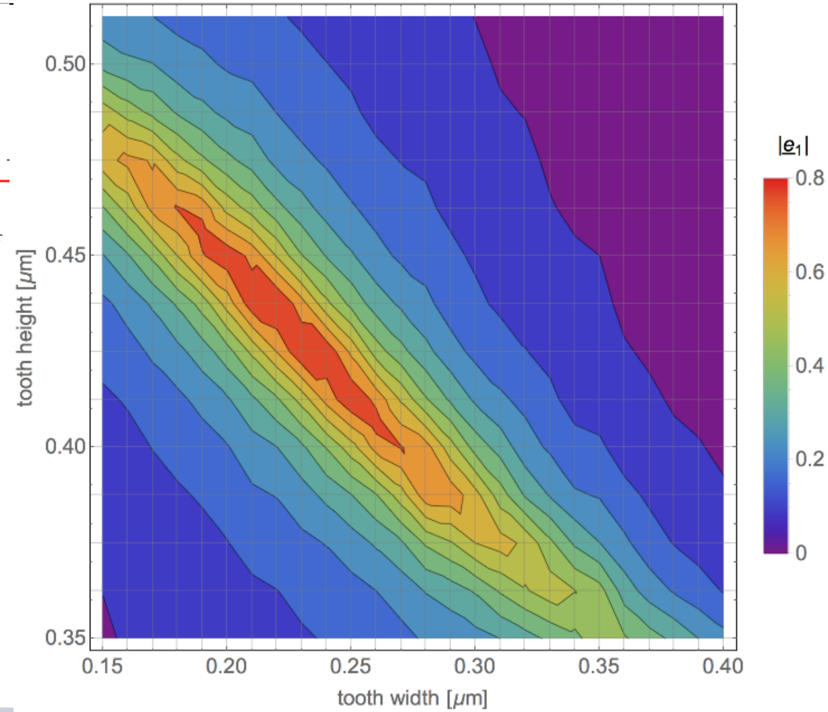
$$\Delta W_{\max} = q\lambda_g|\underline{e}_m|$$

Single DLA cell optimization process

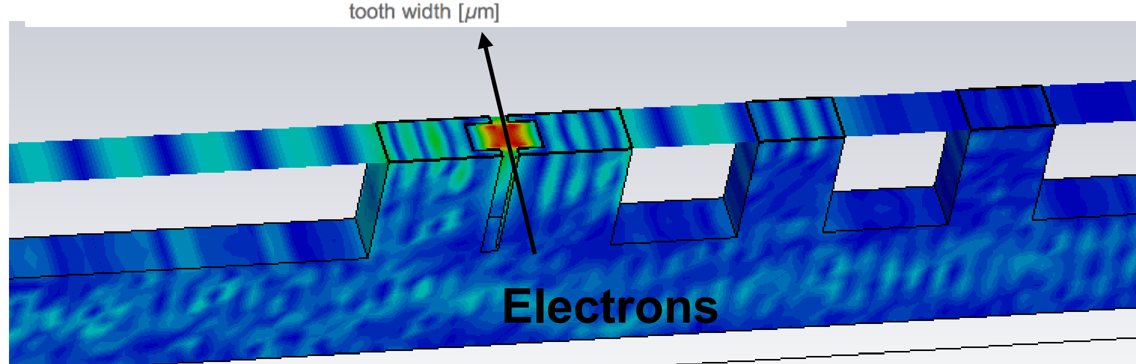






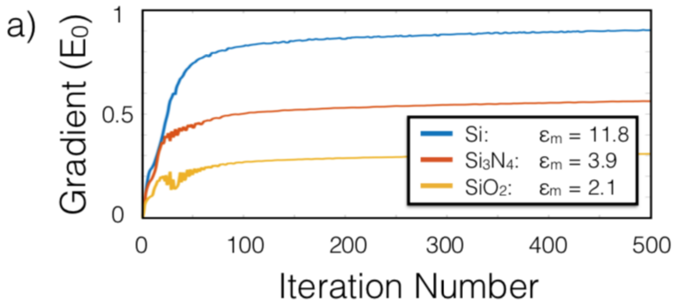


T. Egenolf,
TU Darmstadt

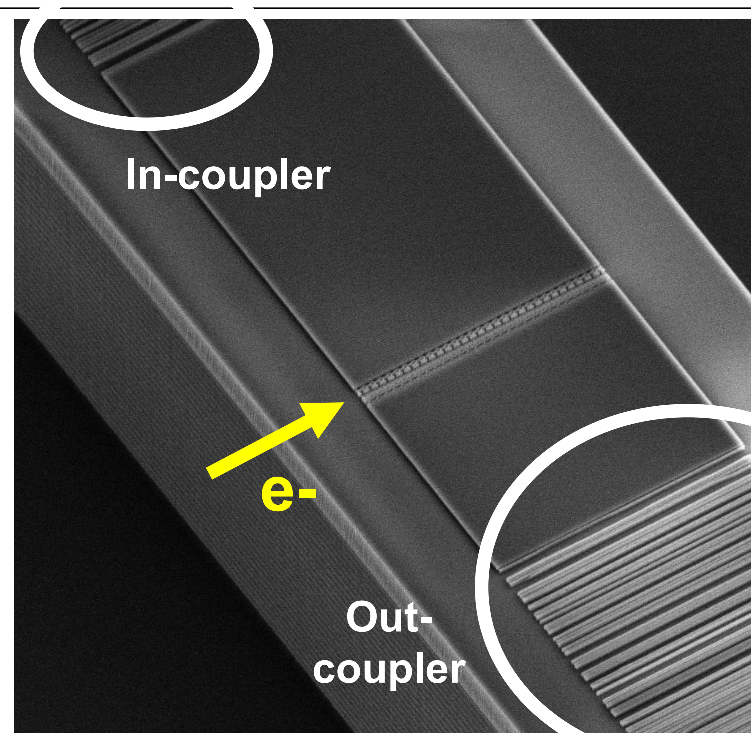


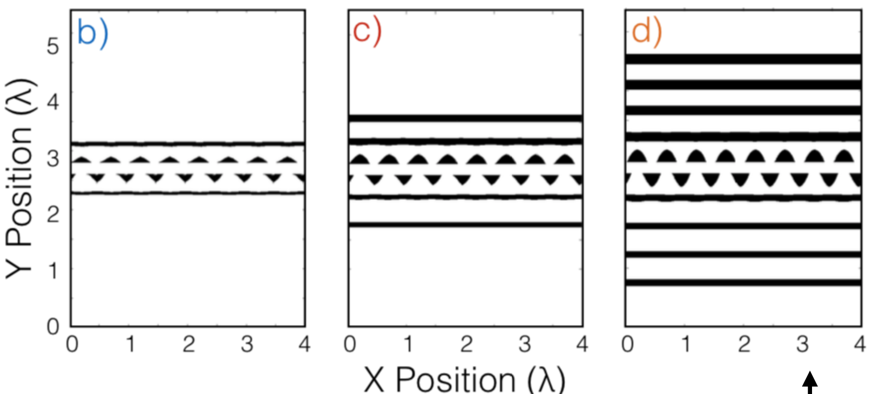
Advanced Optimization Schemes

Inverse Design by Adjoint Variable Method (AVM)

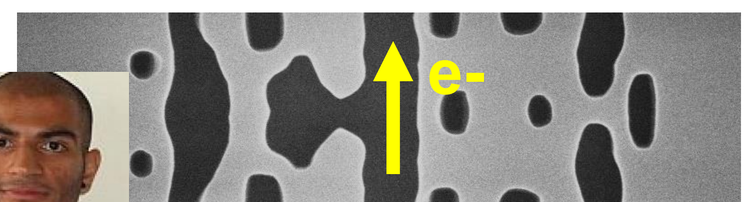


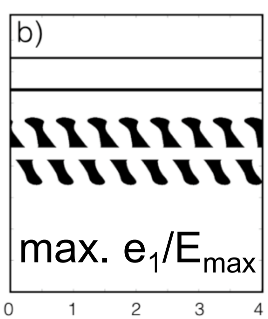
T. Hughes et al.
Opt. Expr.
21, 19 (2017)

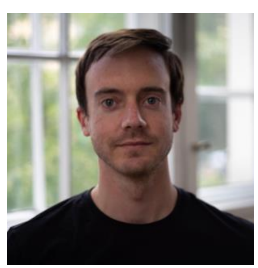




max. e_1







T Hughes,
N. Sapra,
Ginzton Lab,
Stanford

N. Sapra el al.
https://arxiv.org/abs/1808.07630

Bottom-Up design of DLA structures: ***DLAtrack6D***

- One kick per grating cell **(numerically lightweight)**
- **Symplectic code** → No artificial emittance increase

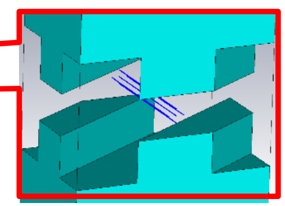
- Kicks by resonant Fourier coefficient

$$\underline{e}_1(x,y) = \underline{e}_1(0,0)\cosh(ik_y y)e^{ik_x x}$$

- Transverse kick by Panofsky-Wenzel theorem

$$\Delta\vec{p}_\perp(x,y;s) = -\nabla_\perp \int \mathrm{d}s\, \Delta p_{||}(x,y;s) = \frac{q\lambda_g\lambda_0}{2\pi c}\Im\left\{e^{2\pi i \frac{s}{\lambda_\mathrm{g}}}\nabla_\perp \underline{e}_1\right\}$$

- Can be applied to laterally coupled structures
  - Subrelativistic structures / Relativistic structures
  - Tilted grating structures
  - Alternating phase / Spatial Harmonic focusing structures



U. Niedermayer et al. Phys. Rev. Accel. Beams **20**, 111302 (2017)

DLAtrack6D

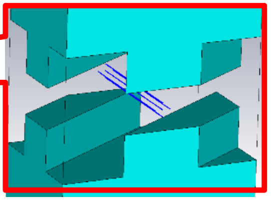
→One kick per grating period

$$x' = \frac{p_x}{p_{z0}}\,,\quad \Delta x' = \frac{\Delta p_x(x,y,\varphi)}{p_{z0}}\,,\quad y' = \frac{p_y}{p_{z0}}\,,\quad \Delta y' = \frac{\Delta p_y(x,y,\varphi)}{p_{z0}}$$

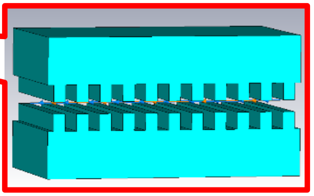
$$\varphi = 2\pi\frac{s}{\lambda_{gz}}\,,\quad \delta = \frac{W-W_0}{W_0}\,,\quad \Delta\delta = \frac{\Delta W(x,y,\varphi)-\Delta W(0,0,\varphi_s)}{W_0}$$

$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ \varphi \\ \delta \end{pmatrix}^{(n+1)} = \begin{pmatrix} x \\ Ax' + \Delta x'(x,y,\varphi) \\ y \\ Ay' + \Delta y'(x,y,\varphi) \\ \varphi \\ \delta + \Delta\delta(x,y,\varphi;\varphi_s) \end{pmatrix}^{(n)} + \begin{pmatrix} \lambda_{gz}x'(x,y,\varphi) \\ 0 \\ \lambda_{gz}y'(x,y,\varphi) \\ 0 \\ -\frac{2\pi}{\beta^2\gamma^2}\delta(x,y,\varphi) \\ 0 \end{pmatrix}^{(n+1)}$$

$$\Delta x' = -\frac{q\lambda_0}{p_{z0}c}\tan(\alpha)\cosh(ik_y y)\Re\left\{\underline{e}_1 e^{i\varphi+i\frac{2\pi x}{\lambda_{gx}}}\right\}$$



$$\Delta y' = \frac{-ik_y\lambda_0^2 q\beta}{2\pi p_{z0}c}\sinh(ik_y y)\Im\left\{\underline{e}_1 e^{i\varphi+i\frac{2\pi x}{\lambda_{gx}}}\right\}$$



$$\Delta\delta = \frac{q\lambda_{gz}}{\gamma m_e c^2}\Re\left\{\underline{e}_1\left(\cosh(ik_y y)e^{i\varphi+i\frac{2\pi x}{\lambda_{gx}}} - e^{i\varphi_s}\right)\right\}$$

U. Niedermayer et al. Phys. Rev. Accel. Beams **20**, 111302 (2017)

Contents

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Stabilization and scalability of DLA

- Magnetic focusing is too weak to counteract acceleration defocusing (see e.g. Ody et al. NIM A 865, 75-83 (2017))

- Spatial harmonic focusing in travelling wave structures
  - see B. Naranjo et al., PRL 109, 1 (2012) → Galaxie DLA
  - Shows only stability, not what emittance fits into the tiny aperture

- Focusing in laterally coupled (standing wave) structures
  - Programmable Spatial Light Modulator (SLM)
  - Small drift sections → Alternating Phase Focusing (APF)

U. Niedermayer et al. accepted for publication in PRL. (see arXiv 1806.07287)

Alternating Phase Focusing (APF)

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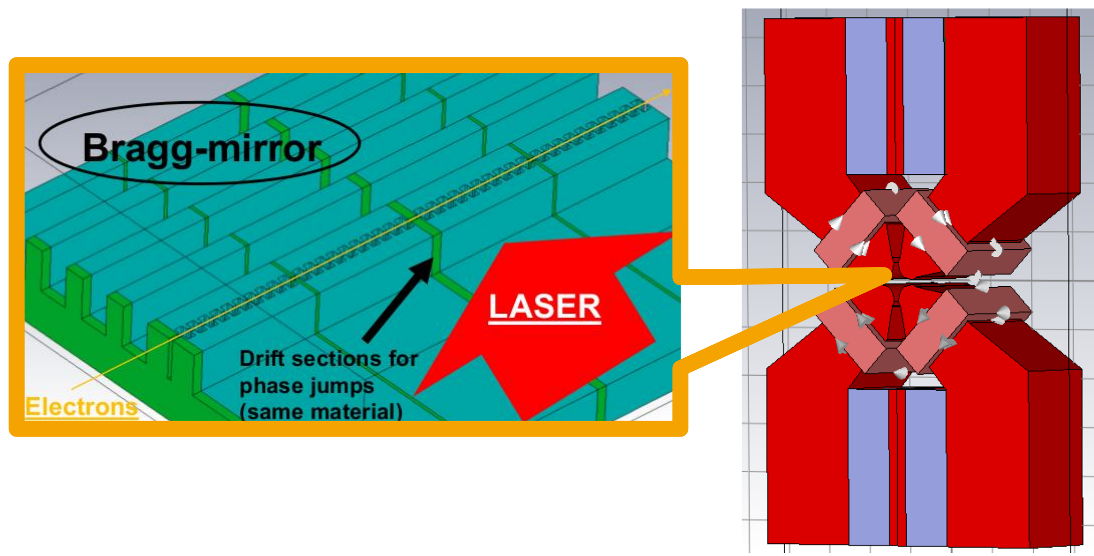
- Originally invented for conventional RF-ion-linacs in the 1950‘ , but outperformed by RFQ
- “Earnshaw‘s theorem“ forbids simultaneous focusing in all directions
- We cannot make 3D structures on the μ-chip scale
- APF lattice is 2D: Possible to fabricate by lithographic methods

Constant focusing in z
Alternating in x and y



Constant focusing in x
Alternating in z and y

Hamiltonian (dual pillar structure)

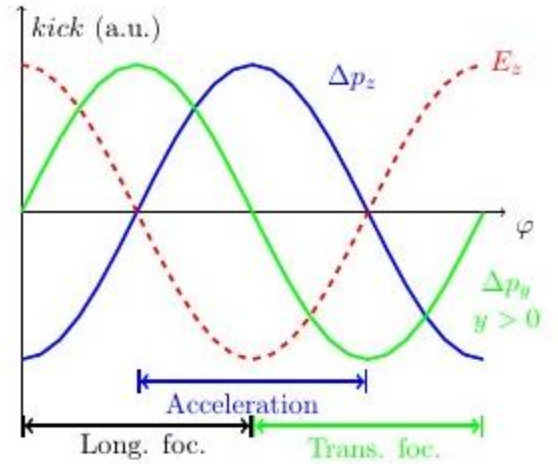
Read off directly from symplectic tracking scheme:

$$\dot{y} = \frac{p_y}{m_e \gamma}$$

$$\dot{p}_y = -q e_1 \frac{\lambda_{gz}}{2\pi} \frac{\omega}{\beta\gamma c} \sinh\left(\frac{\omega y}{\beta\gamma c}\right) \sin\left(\frac{2\pi s}{\lambda_{gz}}\right)$$

$$\dot{s} = \frac{\Delta p_z}{m_e \gamma^3}$$

$$\dot{\Delta p_z} = q e_1 \left[\cosh\left(\frac{\omega y}{\beta\gamma c}\right) \cos\left(\frac{2\pi s}{\lambda_{gz}}\right) - \cos\varphi_s\right].$$



“Earnshaw‘s theorem“

$$H = \frac{1}{2 m_e \gamma}\left(p_x^2 + p_y^2 + (\Delta p_z/\gamma)^2\right) + V$$

Panofsky-Wenzel: $\vec{F} = -\nabla' V$

$$V = q e_1 \left[\frac{\lambda_{gz}}{2\pi} \cosh\left(\frac{\omega y}{\beta\gamma c}\right) \sin\left(\frac{2\pi s}{\lambda_{gz}}\right) - s\cos\varphi_s\right]$$

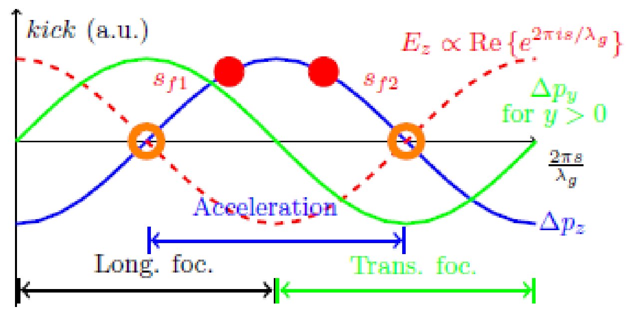
U. Niedermayer et al. Phys. Rev. Accel. Beams **20**, 111302 (2017)

Design of an Alternating Phase Focusing Accelerator Chip

- Time dependent potential

$$V = q\Im\{e_1[\frac{\lambda_g}{2\pi}\cosh\left(\frac{\omega y}{\beta\gamma c}\right)e^{2\pi i s/\lambda_g} - i s e^{i\varphi_s}]\}$$

$$\varphi_s^{(n)} = \varphi_0 - \arg(e_1)^{(n)} \qquad \varphi_0 = \arccos\left[\frac{m_e c^2}{q\lambda_0}\frac{\gamma^3}{|e_1|}\frac{\Delta\lambda_g}{\lambda_0}\right]$$

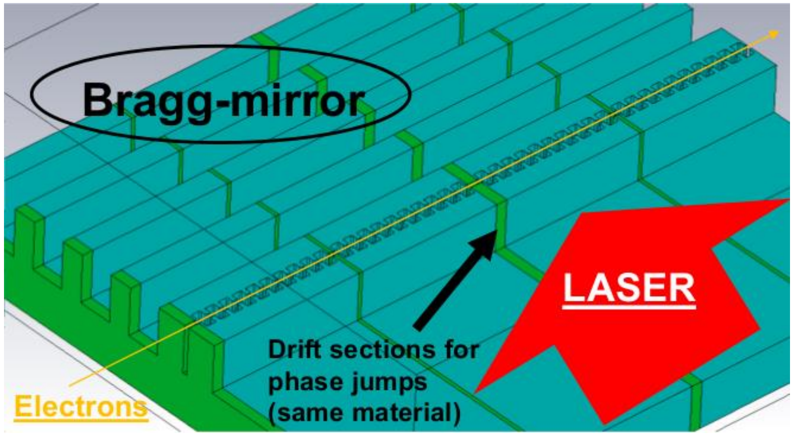


$$V(x,y,s=s_{f1}+\Delta s) = -V(x,y,s=s_{f2}+\Delta s)$$
$$= \frac{q|e_1|\lambda_g}{2\pi}\left[\frac{1}{2}\left(\frac{\omega y}{\beta\gamma c}\right)^2 - \frac{1}{2}\left(\frac{2\pi}{\lambda_g}\Delta s\right)^2\right]\sin(\varphi_0)$$

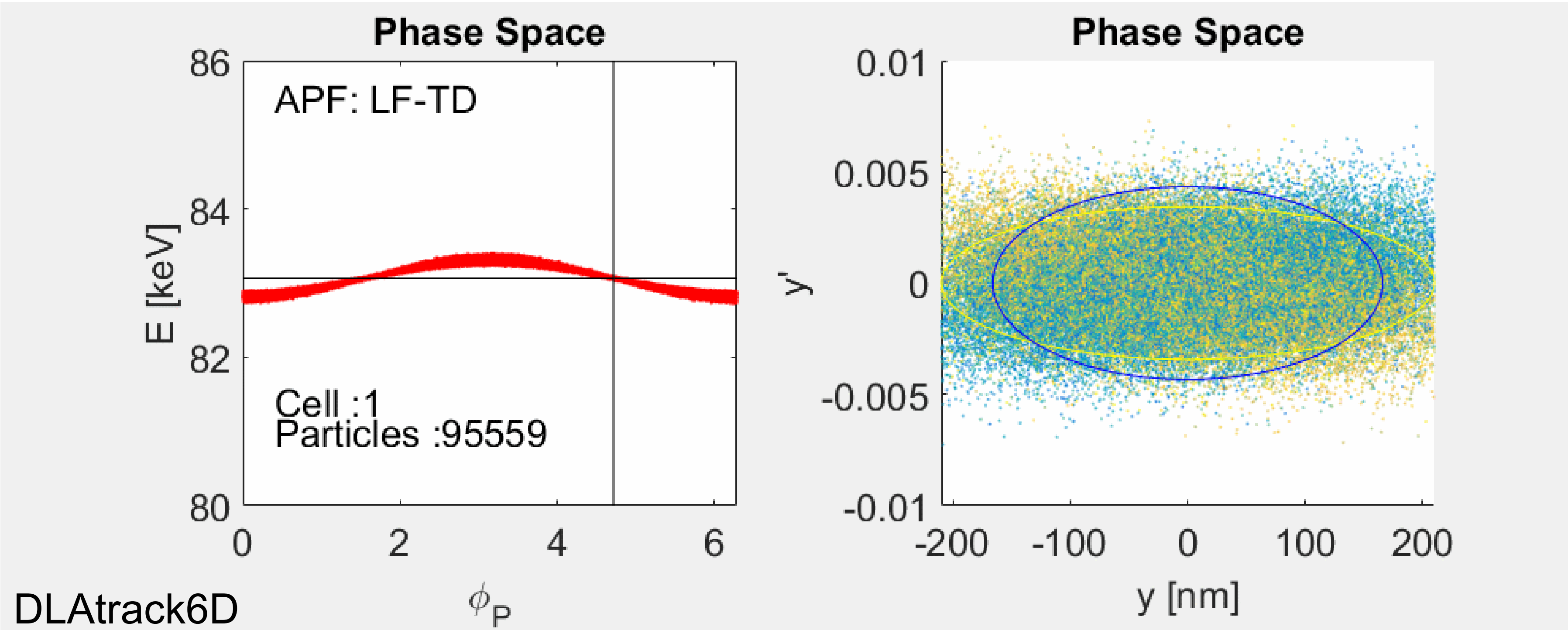
$$y'' + Ky = 0$$
$$\Delta s'' - K\Delta s = 0$$

$$K = \frac{|q|\omega e_1}{(m_e\beta^3\gamma^3c^3)}\sin(\varphi_s)$$

$$\arg(e_1)(P) = \begin{cases} 0, P \text{ odd} \\ 2\varphi_0, P \text{ even} \end{cases}$$



Unbunched transversely matched



$$\varepsilon(y, y') = \hat{\gamma} y^2 + 2\hat{\alpha} y y' + \hat{\beta} y'^2$$

Longitudinal Courant-Snyder Invariant: $\varepsilon_L(\Delta s, \Delta s') = \hat{\gamma}_L \Delta s^2 + 2\hat{\alpha}_L \Delta s \Delta s' + \hat{\beta}_L \Delta s'^2$

U. Niedermayer et al. accepted for publication in PRL. (see arXiv 1806.07287)

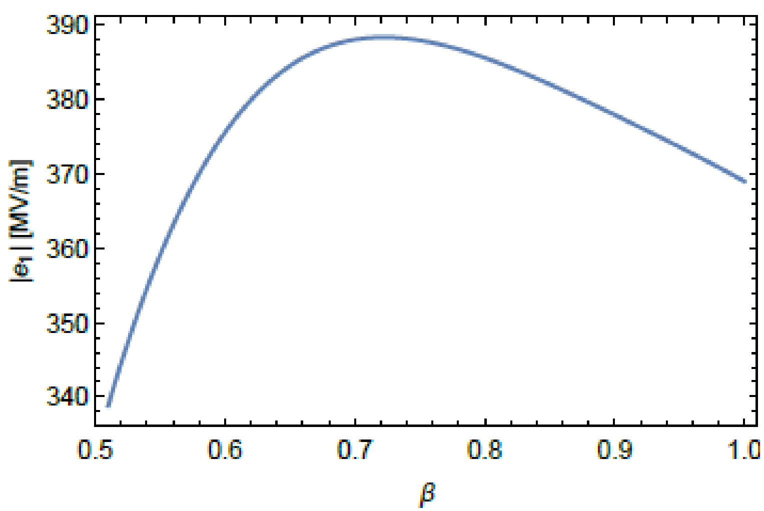
Design of a lattice incl. accleration

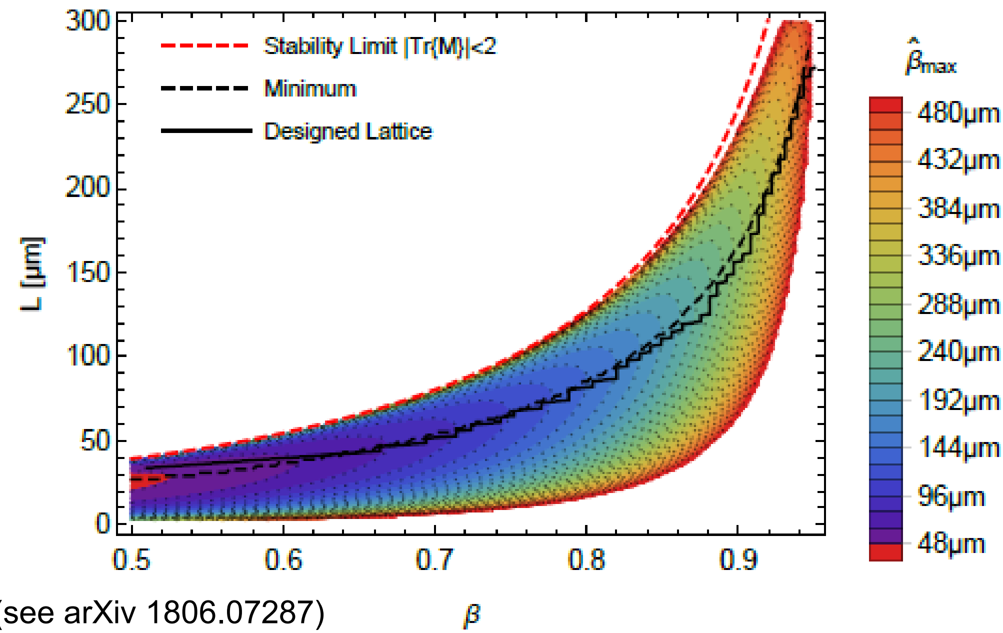
Ramp: $$W_{kin}(N) = W_{kin,0} + q \sum_{n=1}^{N} \lambda_g^{(n)} \Re\{e_1^{(n)} e^{i\varphi_s^{(n)}}\}$$

Length chirp according to $\lambda_g = \beta\lambda_0$: $$\frac{\lambda_g^{(n+1)} - \lambda_g^{(n)}}{\lambda_0} = \beta^{(n+1)} - \beta^{(n)} = \frac{q\lambda_0 \Re\{e_1^{(n)} e^{i\varphi_s^{(n)}}\}}{m_e c^2 \gamma^{(n)3}}$$

Optimization such that

$$\arg(e_1)^{(n)} \neq f(\lambda_g^{(n)})$$





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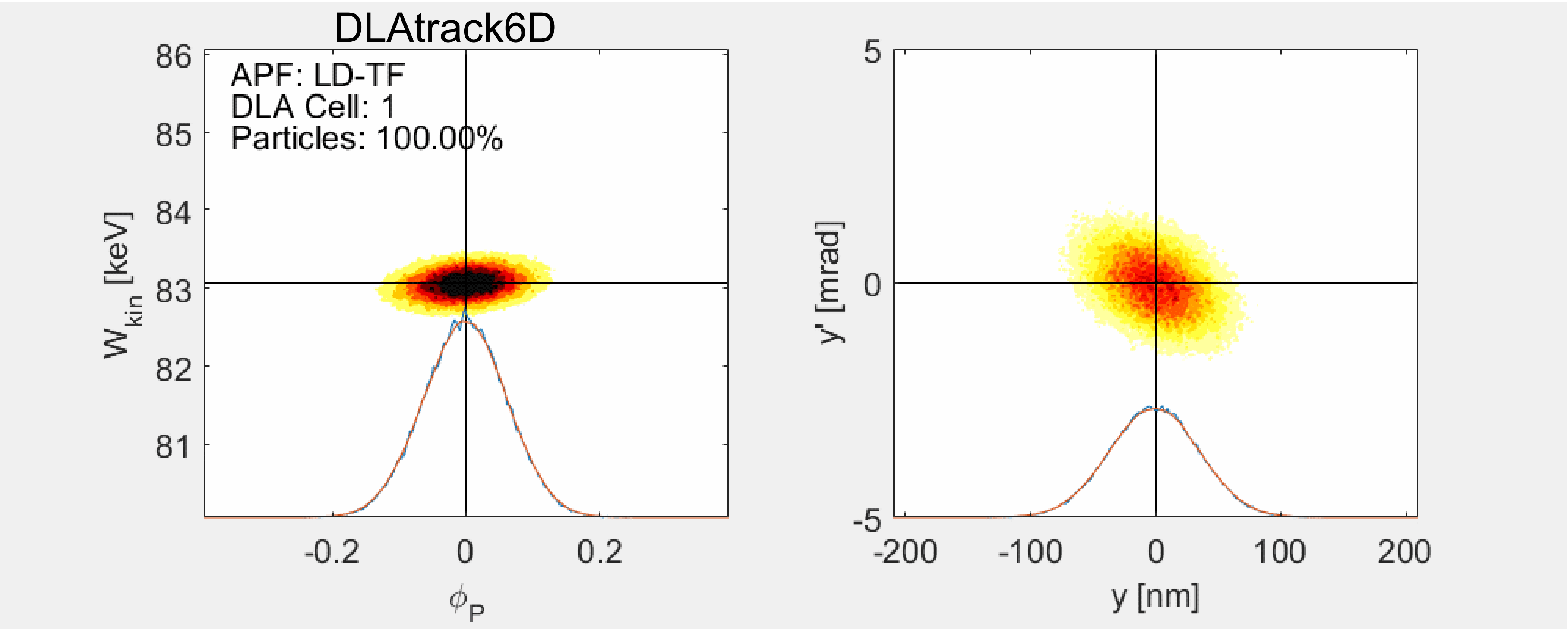
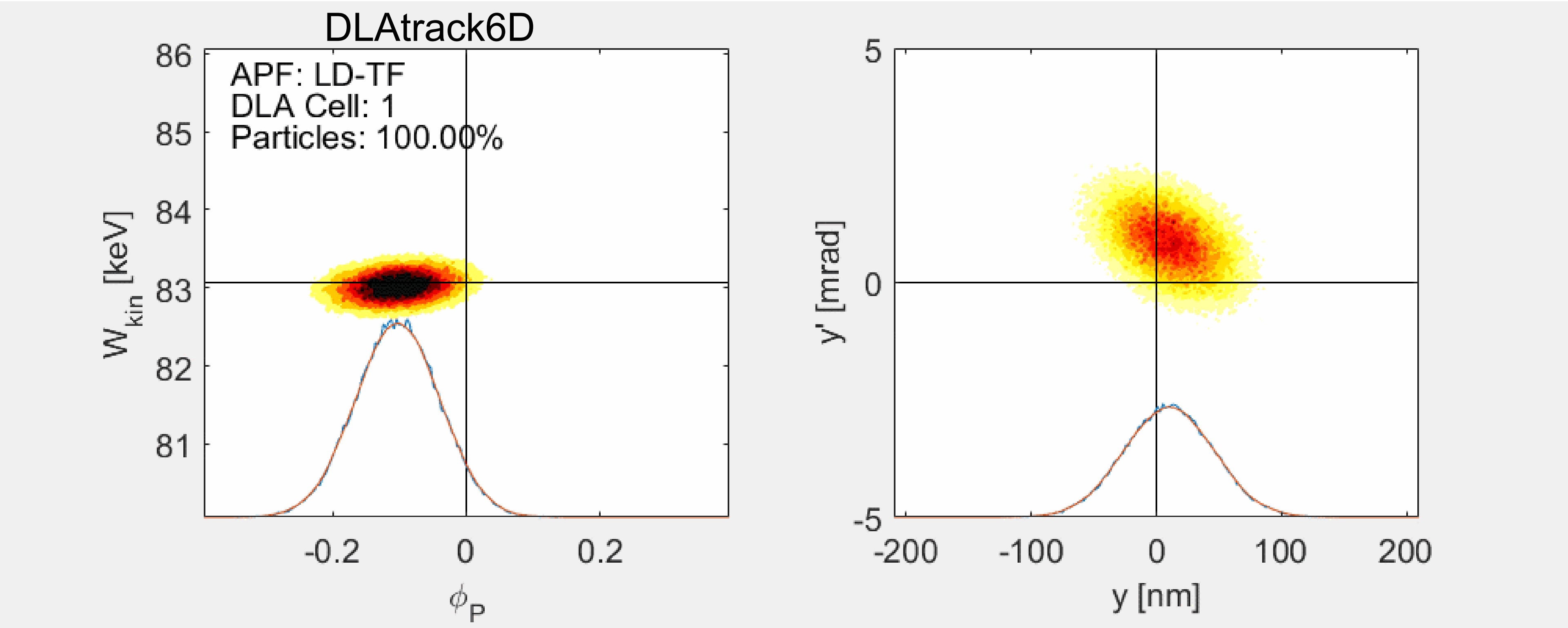
The ideal ACHIP scenario



93% transmission at $\varepsilon = 0.025\ \mathrm{nm}$

U. Niedermayer et al. accepted for publication in PRL. (see arXiv 1806.07287)

Misalignment example

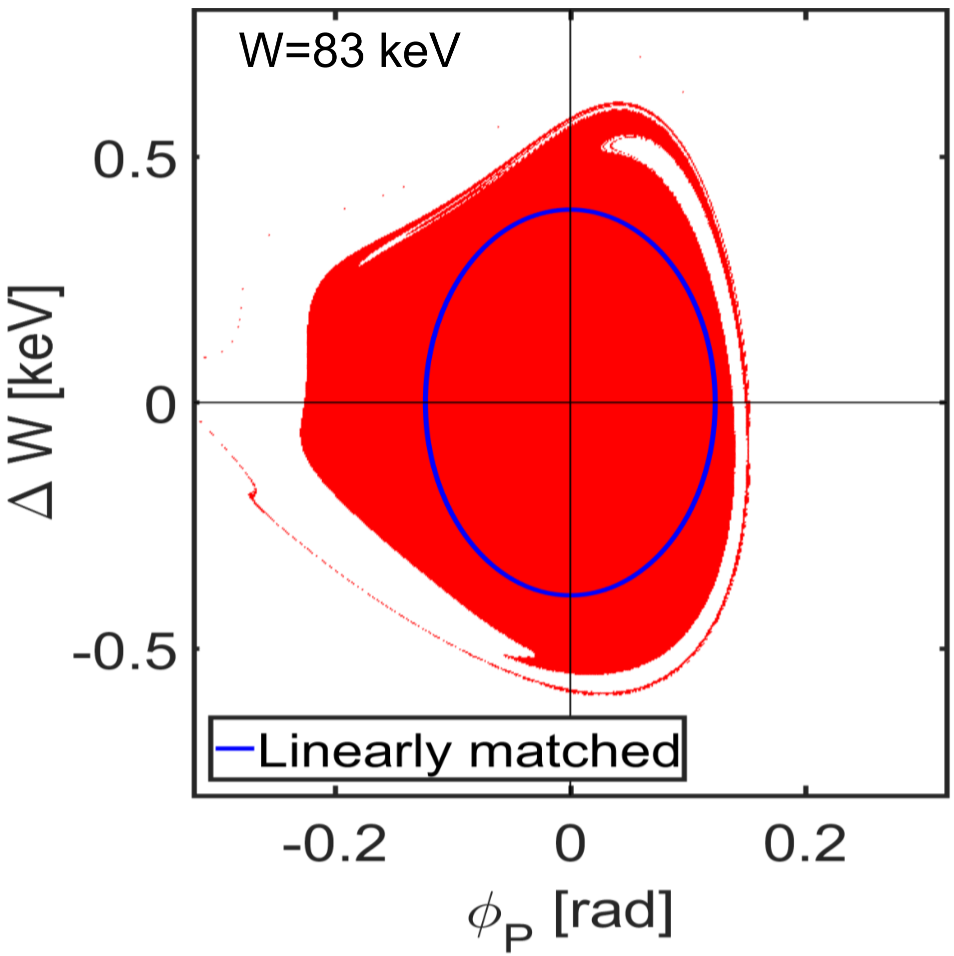


66% transmission at $\varepsilon = 0.025\ \mathrm{nm}$

<u>Initial mismatch:</u>

- y=10 nm y‘=1 mrad
- Phi_P=0.1 rad Delta_W=0

Initial phase space



Longitudinal matching condition:

$$\frac{\sigma_\varphi}{2\pi} = \frac{\hat{\beta}_L}{\beta^3\gamma^3\lambda_0}\frac{\sigma_{\Delta W}}{m_e c^2}$$

$$\hat{\alpha}_L = 0$$

Bunch length (numerically) :

$$4\sigma_z = 40 \text{ nm}$$

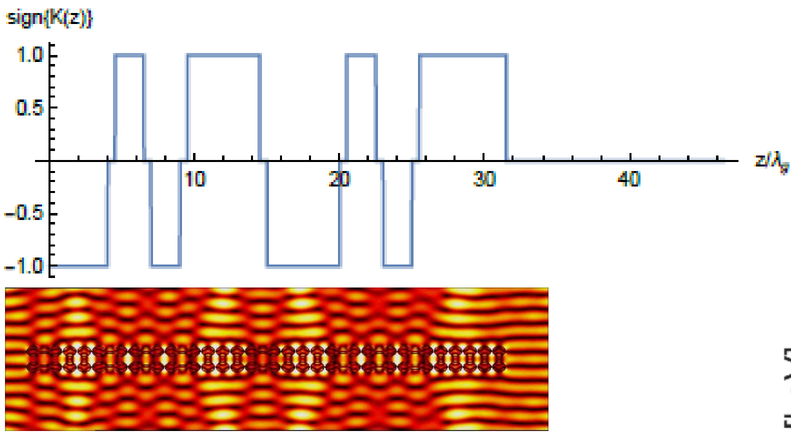
Transverse matching condition:

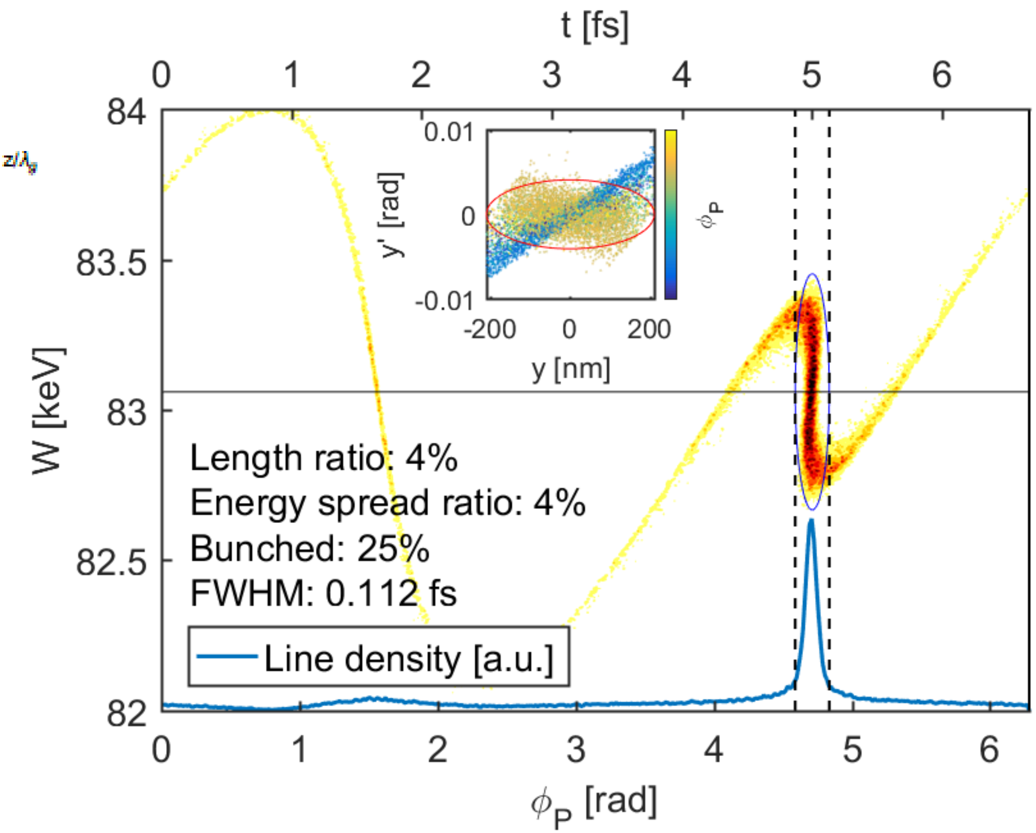
$$\sigma_y = \sqrt{\hat{\beta}\varepsilon}$$

$$\hat{\alpha} = 0 \Rightarrow \sigma_{y'} = \sqrt{\varepsilon/\hat{\beta}}$$

U. Niedermayer et al. accepted for publication in PRL. (see arXiv 1806.07287)

Bunching



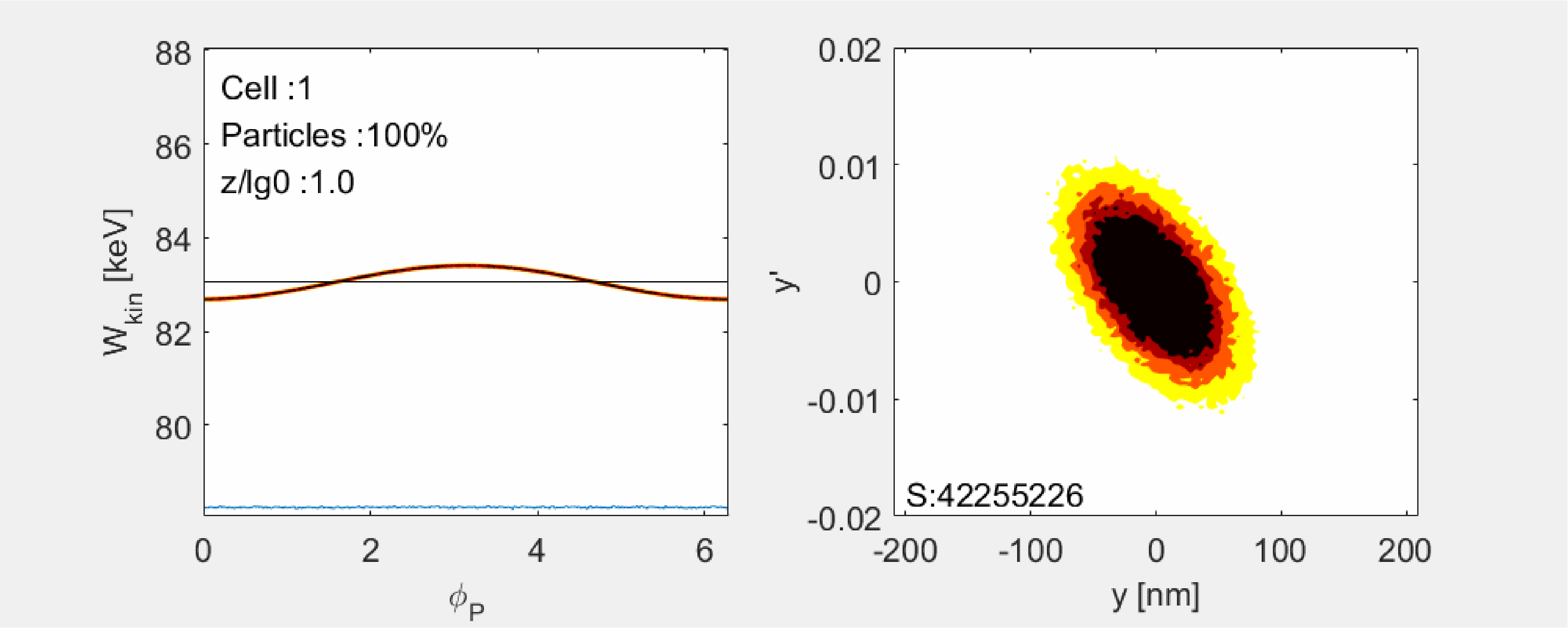


- **~0.1 fs bunches**
- Low (matched) energy spread
- Transverse confinement

$$\mathrm{M}_b = \mathrm{M}_\mathrm{o}^{30}\mathrm{M}_\mathrm{f}^{6}\mathrm{M}_\mathrm{o}\mathrm{M}_\mathrm{d}^{2}\mathrm{M}_\mathrm{o}\mathrm{M}_\mathrm{f}^{2}\mathrm{M}_\mathrm{o}\mathrm{M}_\mathrm{d}^{5}\mathrm{M}_\mathrm{o}\mathrm{M}_\mathrm{f}^{5}\mathrm{M}_\mathrm{o}\mathrm{M}_\mathrm{d}^{2}\mathrm{M}_\mathrm{o}\mathrm{M}_\mathrm{f}^{2}\mathrm{M}_\mathrm{o}\mathrm{M}_\mathrm{d}^{4}$$

U. Niedermayer et al. accepted for publication in PRL. (see arXiv 1806.07287)

Bunching



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Contents

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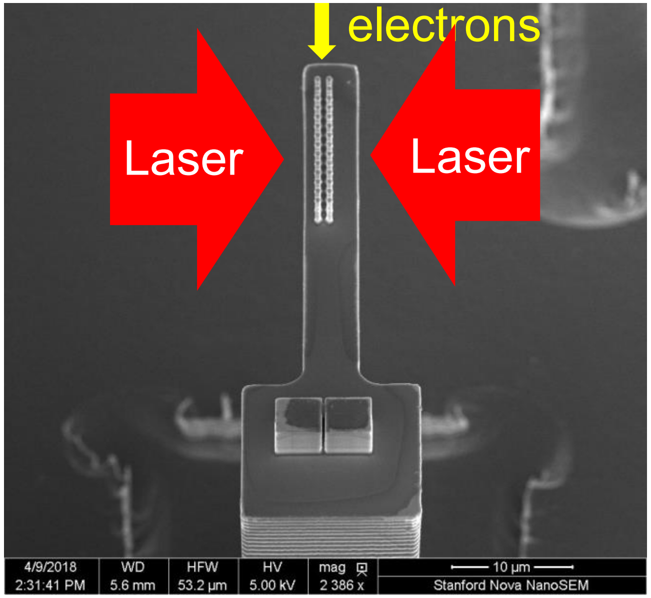
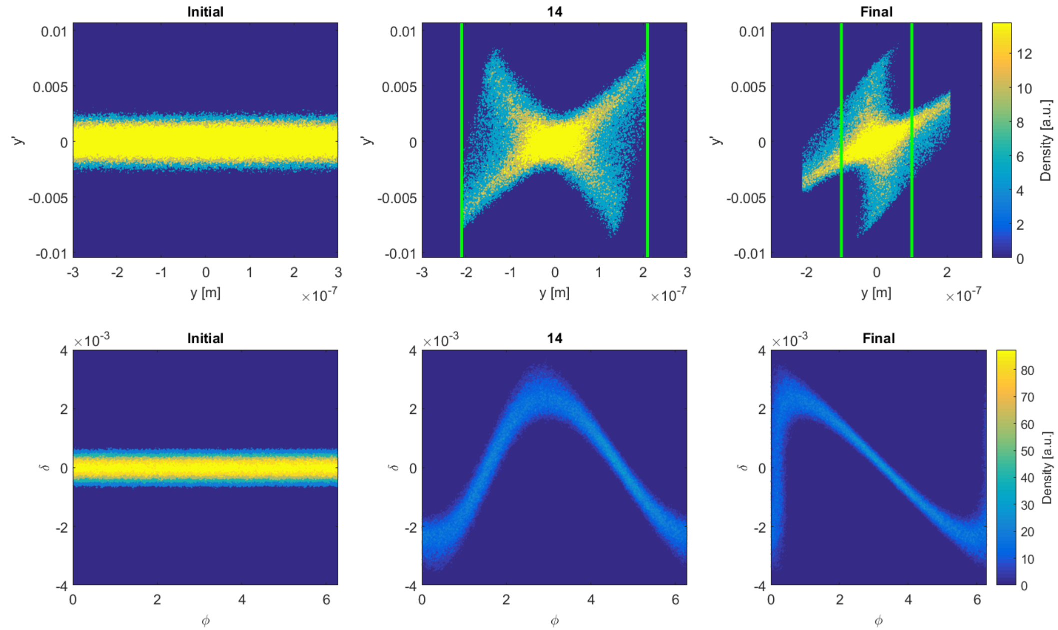
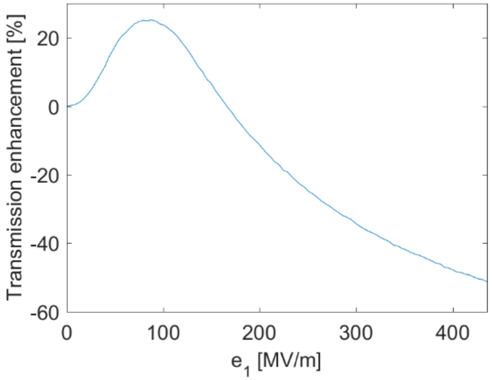
Single stage focusing experiment with aperture





Data has been taken, publication almost ready

Dylan Black, Stanford



U. N. DLAtrack6D simulation

preliminary

Buncher / streaker experiment at Stanford

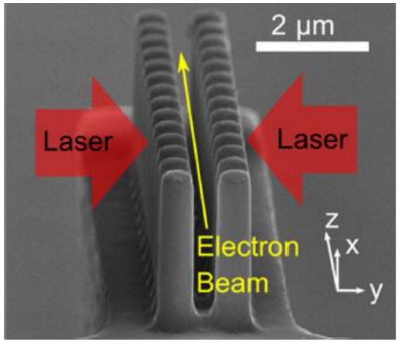
Symmetric DLA in out of phase mode:

$$\underline{e}_1(x,y) = \underline{e}_1(0,0)\,{\color{red}\sinh}(ik_y y)e^{ik_x x}$$

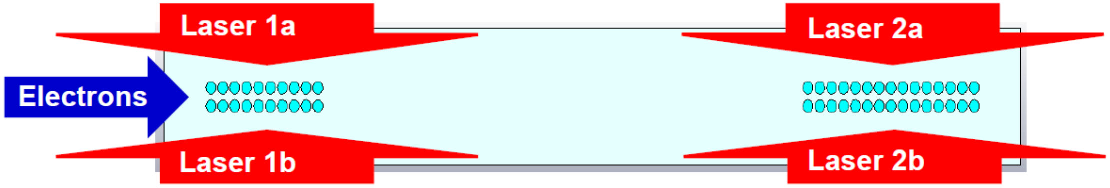
$$\Delta y' = \frac{-ik_y\lambda_0^2 q\beta}{2\pi p_{z0}c}\cosh(ik_y y)\Im\left\{\underline{e}_1 e^{i\varphi}\right\}$$

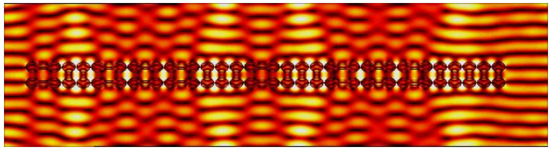
$$\Delta\delta = \frac{q\lambda_{gz}}{\gamma m_e c^2}\sinh(ik_y y)\Re\left\{\underline{e}_1 e^{i\varphi}\right\}$$

2 lasers: "incoherent"
Acceleration/streaking



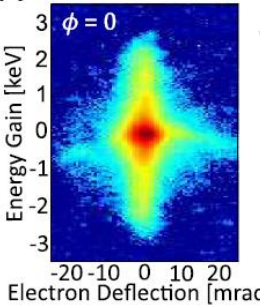
4 lasers allow bunching and coherent streaking:



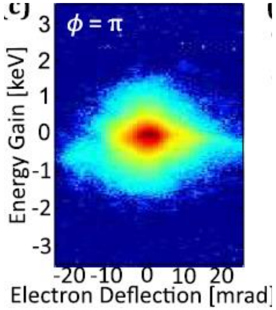


APF buncher:
→ Small energy spread
→ coherent acceleration
→ <u>**All 4 quadrants coherent**</u>!

<u>Acceleration</u>



<u>Streaking</u>



K. Leedle et al.
Optics Letters, 2018

Transport Experiment at FAU Erlangen

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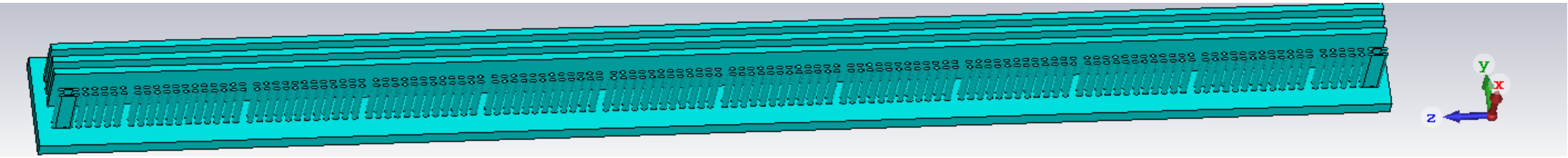
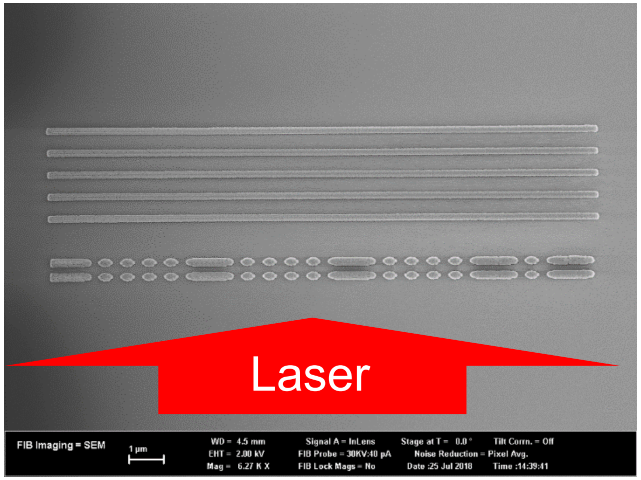


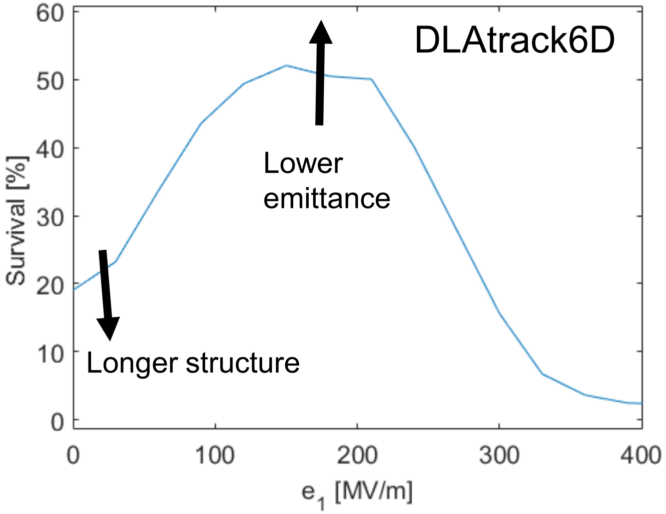
- Fully scalable (lenght independent transmission)
- Limited by x-Rayleigh length 800µm
- Transversly matched (min betafct. ~20µm @ E_L=0.8GV/m)

Multistage focusing:
(Laser on/off contrast)



e_1/E_L~0.25
(incl. DBR)

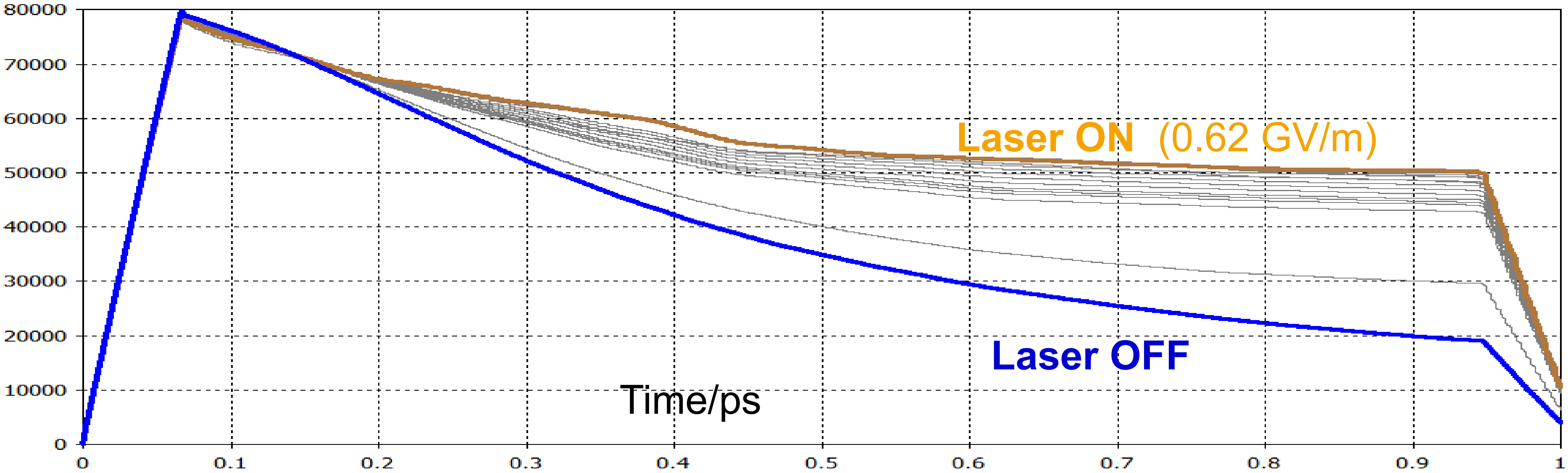
Geo. Emittance 0.3nm
Ekin=26.47keV

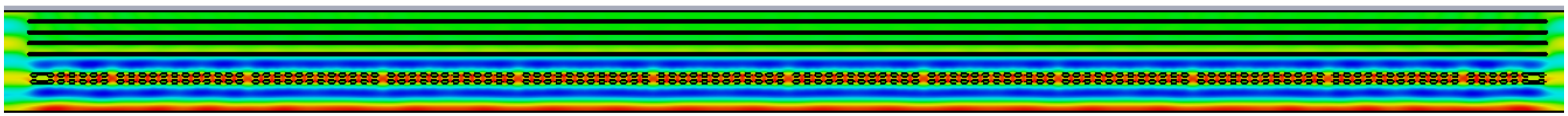


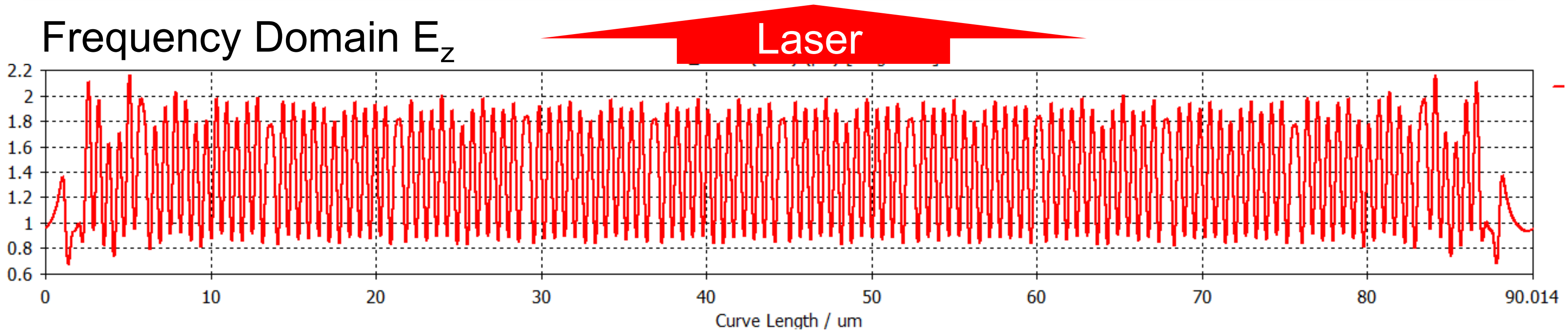
P. Yousefi, J. Illmer:
Fabrication test. Final fab ongoing.

PIC simulation (CST Particle Studio)

100,000 electrons with random phase (uniform dist.)



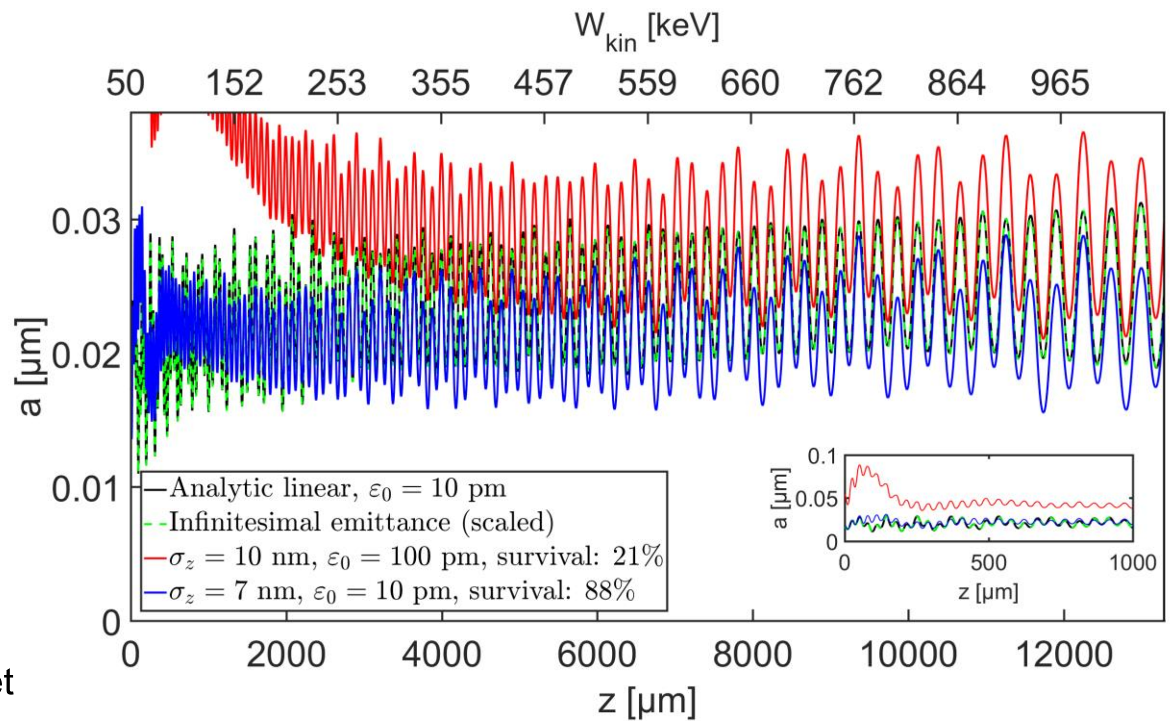


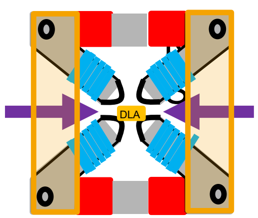


Experiments: Shoebox at Stanford
(a slightly more conservative design)

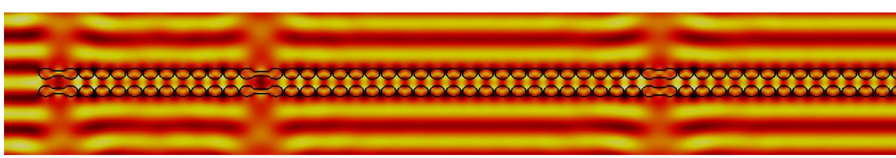
Chirped APF dual pillar grating for acceleration
50keV → 1MeV

- Laser 300 MV/m (2 sides)
- Av. gradient 73 MeV/m
- Length 1.3 cm
- Emittance requirement: **<0.1nm (geo. @ 50keV)**
- Bunch length: **< 40nm**





Quadrupole magnet for focusing in the invariant direction



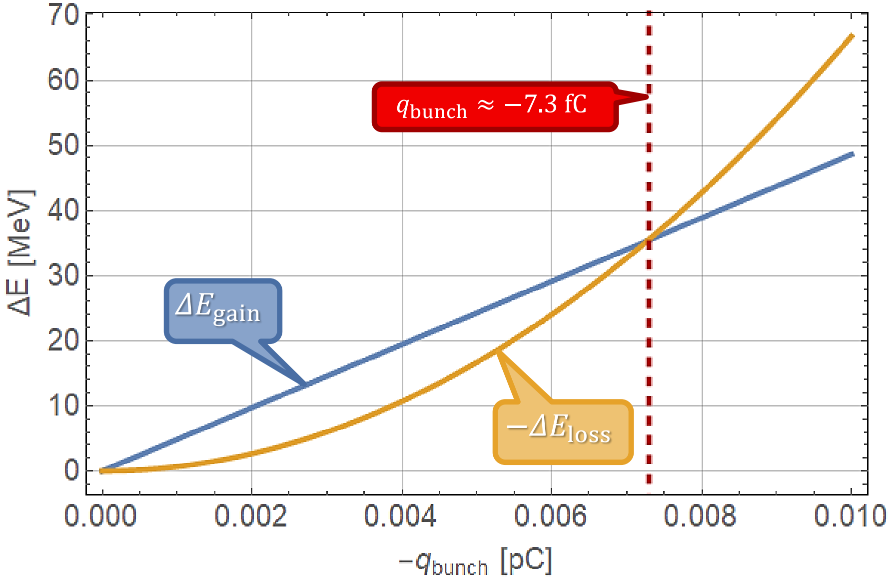
$$B'_{\mathrm{quad}} = 1\ \mathrm{kT/m} \ll B'^{\mathrm{equiv.}}_{\mathrm{APF}} = 5\ \mathrm{MT/m}$$

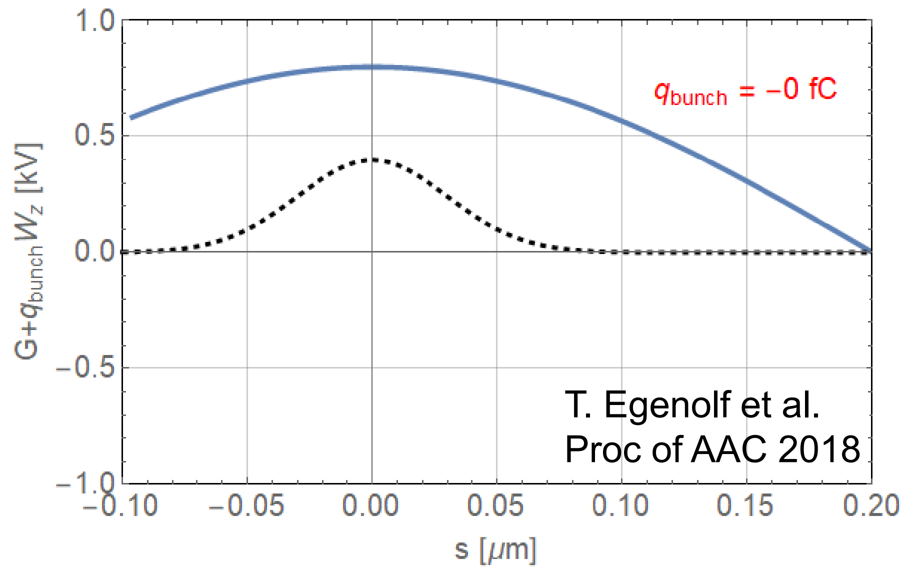
Summary

- Simplified simulations with DLAtrack6D in place
- APF beam dynamics scheme works in theory
  - Overcomes resonant acceleration defocusing problem
  - Can also used for bunching in the attosecond range
- Field flatness needs to be tuned (optimized)
- Quadrupole magnet is being developed

Outlook and Wish List

- Plans are to include wake field kicks in DLAtrack6D





A *moving window* 3D track/PIC code would be nice!
(incl. dielectrics, pulse front tilted laser, open BC)

Thank you for your attention!

The End

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Questions?