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T E M F

MACHINE LEARNING-BASED DIAGNOSTICS AND CONTROL OF DIELECTRIC LASER ACCELERATION

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Joint research project with Luca Genovese and Huseyin Cankaya (DESY / UHH Hamburg)

Bild: Wolfgang Müller

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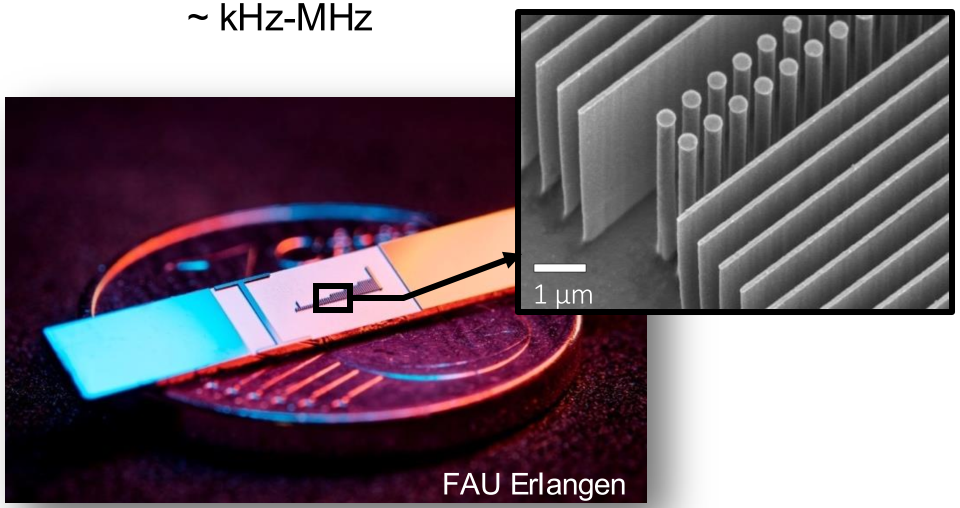
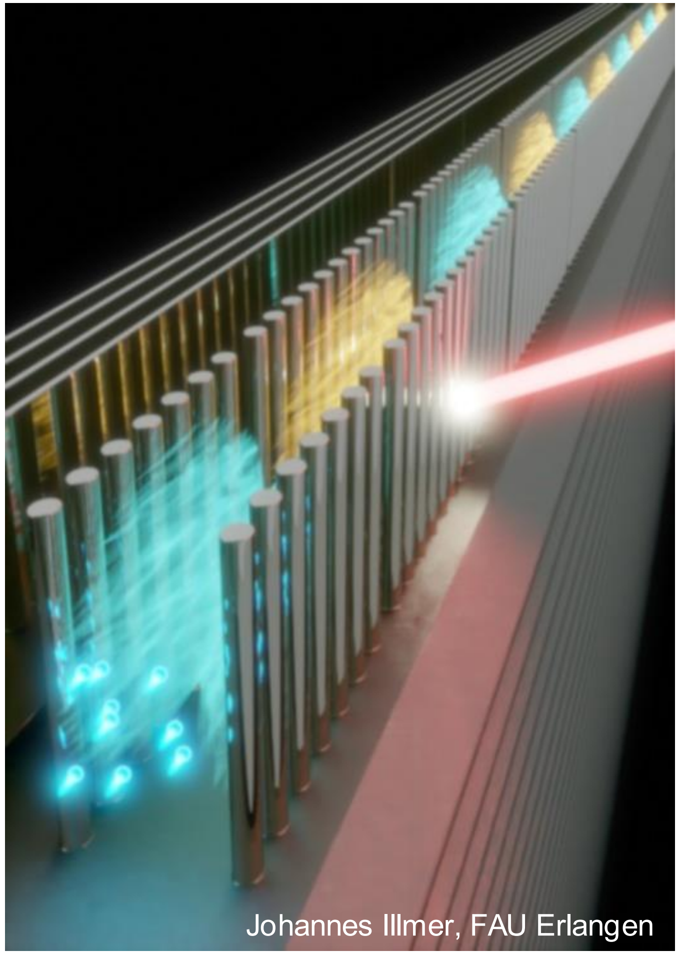
DIELECTRIC LASER ACCELERATION

Dielectrics – Why?

Frequencies	Damage threshold	Acceleration gradient	Beam quality
f = 150 THz (λ=2 μm) τ = 6.6 fs	>3 GV/m fields	>1 GeV/m	Emittance <100 pm rad

Repetition rate
~ kHz-MHz





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DLA IN THEORY

- Proof of principle:

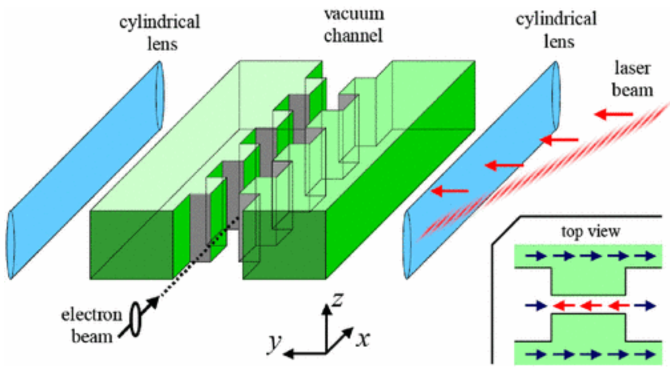
  K. Shimoda, Applieds Optics 1 (1), 33-35 (1962)
  T. Plettner et al., Phys. Rev. ST AB 9, 111301 (2006)

- Structure design and optimization:

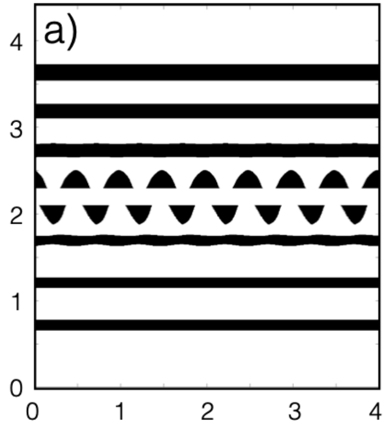
  T. Hughes et al., Optics Express 25 (13), 15414-15427 (2017)
  U. Niedermayer, T. Egenolf et al., PRAB 20, 111302 (2017)

- Guiding by Alternating Phase Focusing:

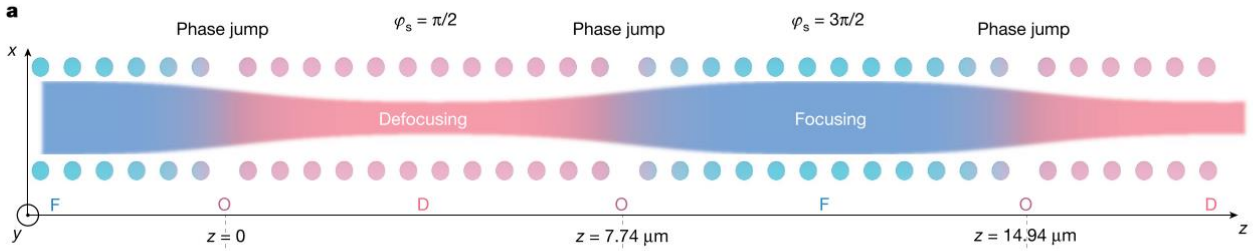
  U. Niedermayer, T. Egenolf et al., PRL 121, 214801 (2018)
  U. Niedermayer, T. Egenolf et al., PRL 125, 164801 (2020)



T. Plettner et al., Phys. Rev. ST AB 9, 111301 (2006)



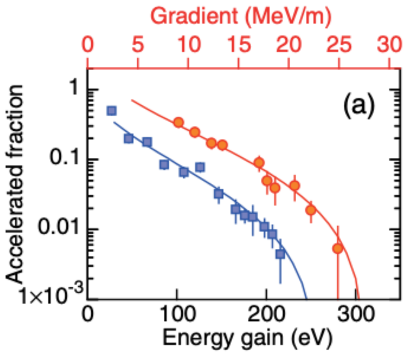
T. Hughes et al., Optical Express 25 (13), 15414-15427 (2017)



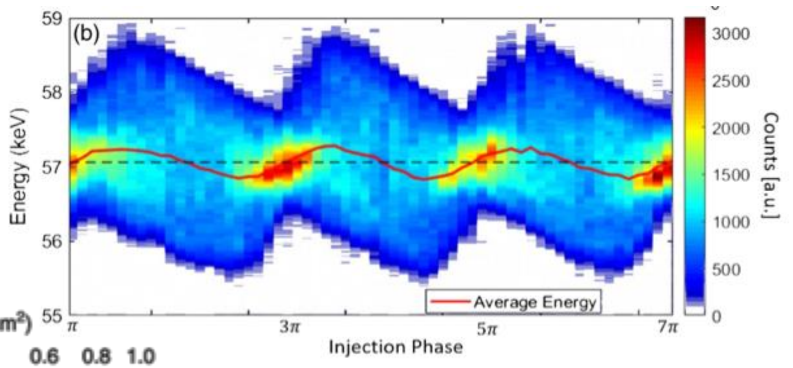
R. Shiloh et al., Nature 597, 498 (2021)

IS IT A REAL ACCELERATOR?

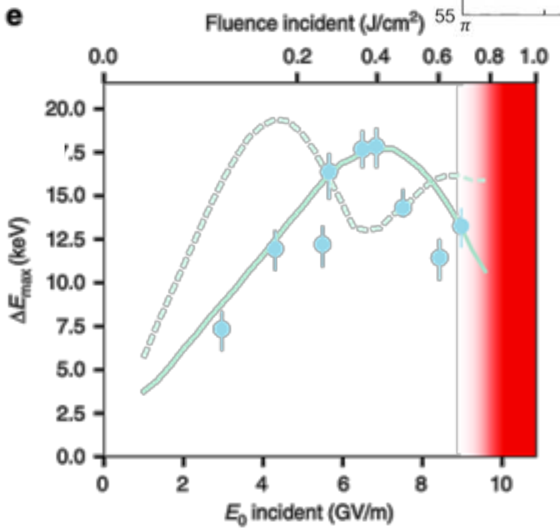
- Proof of principle:
  - J. Breuer, P. Hommelhoff, PRL 111, 134803 (2013)
  - E. A. Peralta et al., Nature 503(7474), 91-94 (2013)
- Acceleration at subrelativistic energies:
  - D. S. Black et al., PRL 123, 264802 (2019)
  - N. Schönenberger et al., PRL 123, 264803 (2019)
- Acceleration at relativistic energies:
  - K. Wootton et al., Opt. Lett. 41 (12), 2696-2699 (2016)
  - D. Cesar et al., Communications Physics 1, 46 (2018)
- Guiding:
  - R. Shiloh et al., Nature 597, 498 (2021)
  - P. Broaddus, T. Egenolf et al., PRL 132, 085001 (2024)



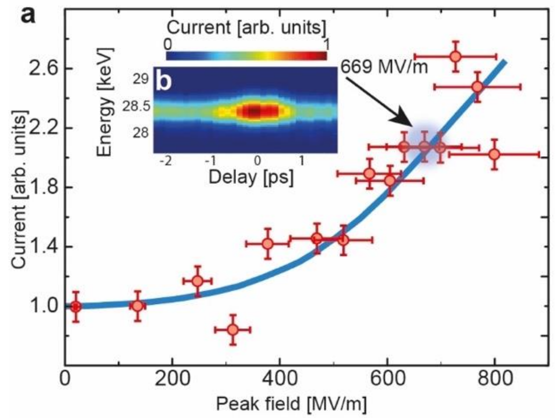
J. Breuer, P. Hommelhoff, PRL 111, 134803 (2013)



D.S. Black et al., PRL 123, 264802 (2019)

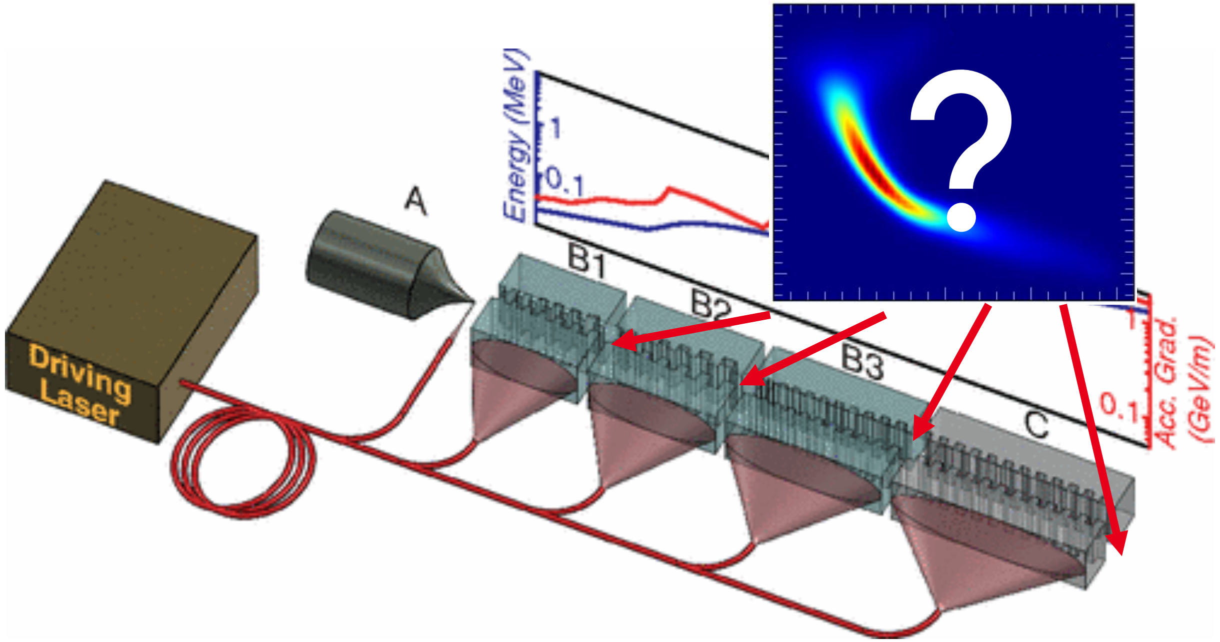


D. Cesar et al., Communications Physics 1, 46 (2018)



R. Shiloh et al., Nature 597, 498 (2021)

MISSING PIECE: DIAGNOSTICS



J. Breuer, P. Hommelhoff, PRL 111, 134803 (2013)

- Diagnostics integrated on a chip
- Temporal resolution: sub-fs
- Spatial resolution: sub-micron
- Best choice: dielectric materials

First idea: Use what is already there

→ Reconstruction

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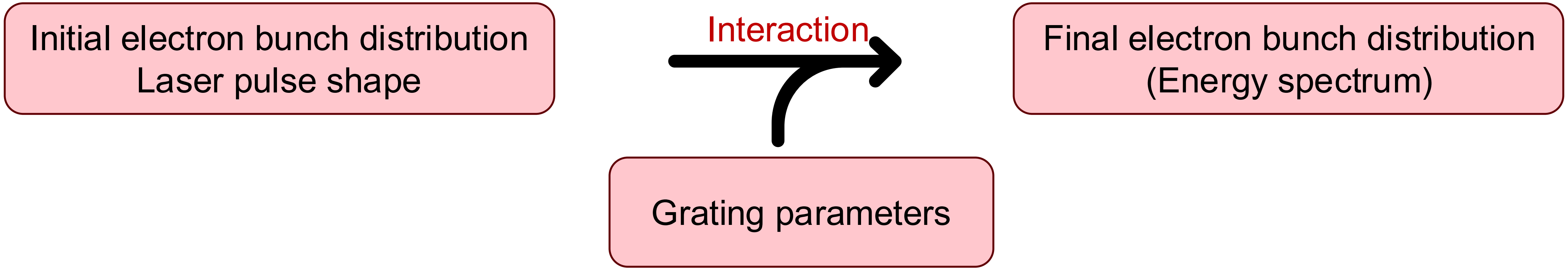
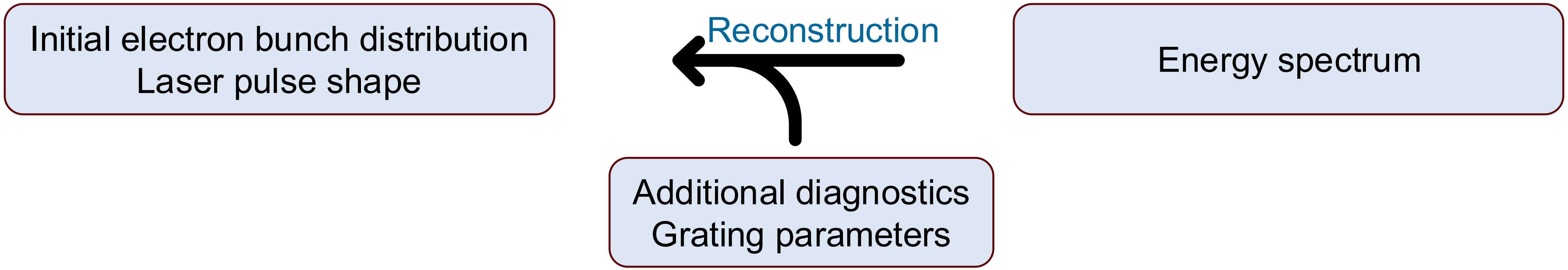
DLA EXPERIMENT

Measurement



Diagnotics



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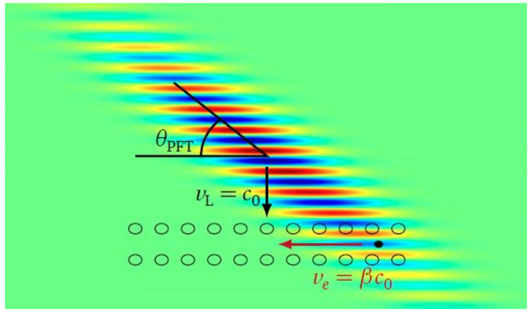
LASER PULSE SHAPING

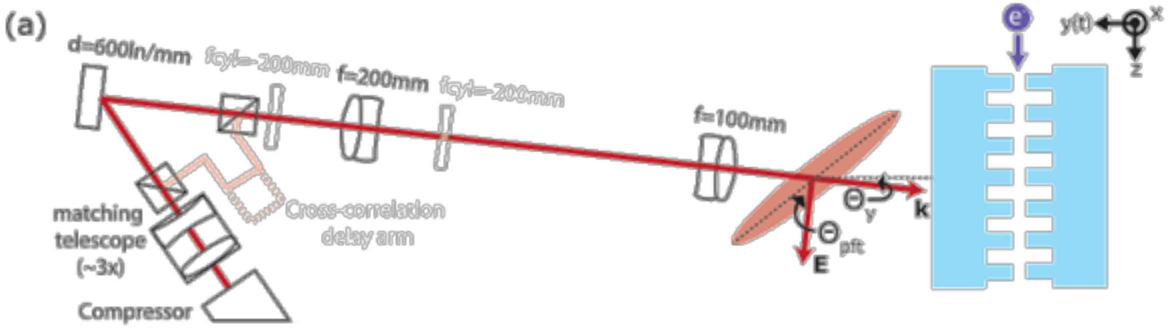
Material damage threshold depends on pulse length

→ Pulse length limited by damage threshold

→ Interaction length limited by pulse length

→ Solution: Pulse front tilt





D. Cesar et al, Optics Express 26, 29216 (2018)

Synchronicity condition: $\beta = \Lambda_p/(\lambda m)$

→ Phase errors due to

- misalignments
- fabrication / design errors
- higher order diffraction
- non-linear effects in the dielectric

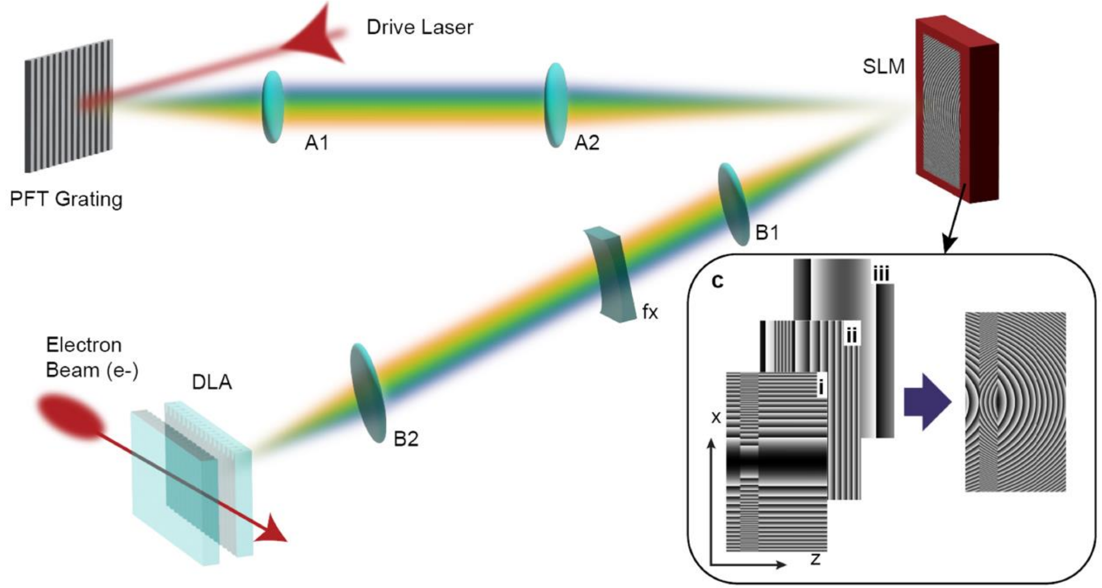
need to be corrected

→ Accelerating non-relativistic electrons requires banana shaped pulse front

→ Solution: Non-linear phase shaping

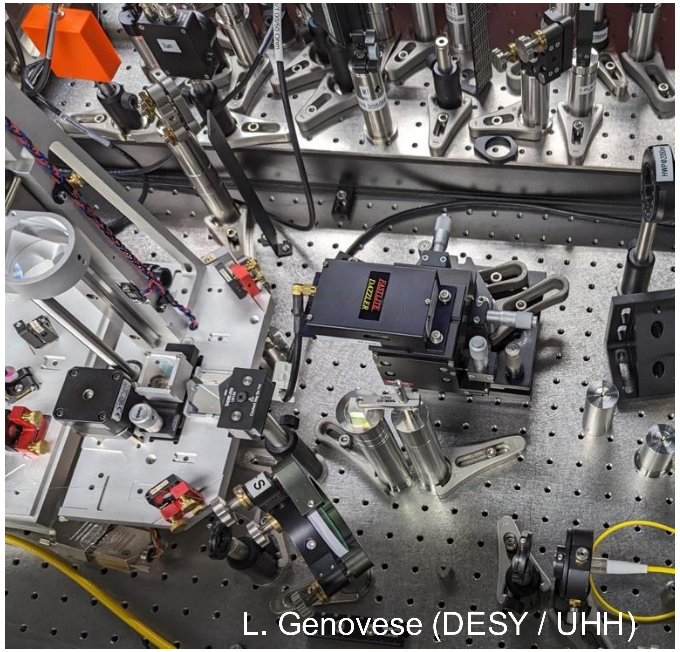
LASER PULSE SHAPING

Spatial light modulator (SLM)



S. Crisp et al., arXiv:2509.08170 (2025)

Acousto-optic programmable diffractive filter (AOPDF)



L. Genovese et al., CLEO, Munich, Germany (2025)

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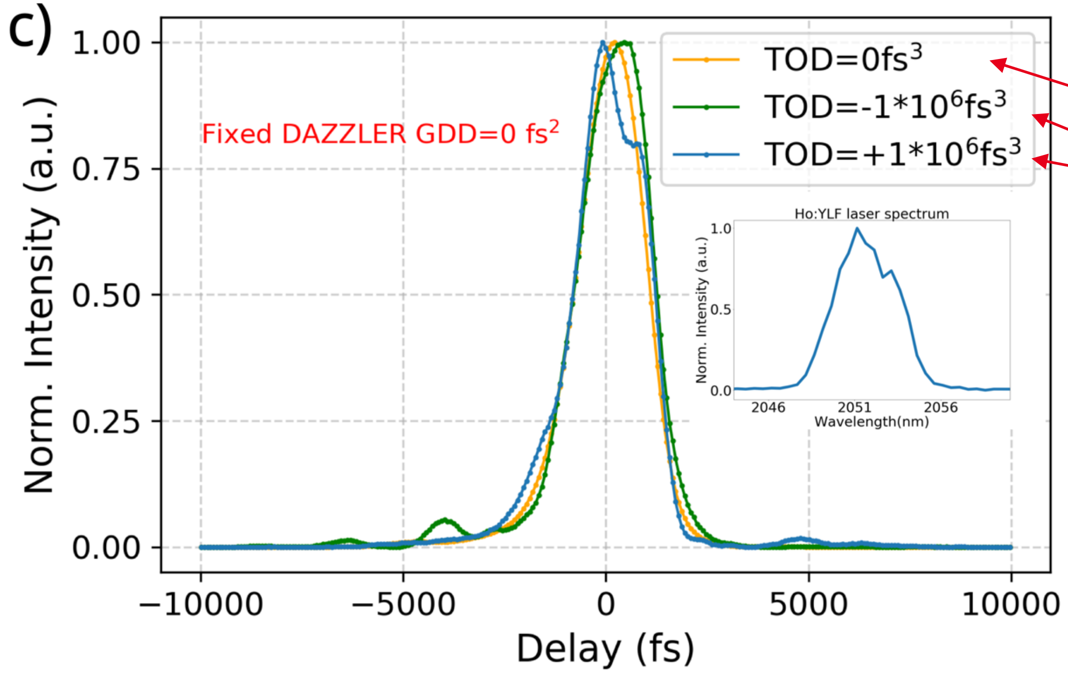
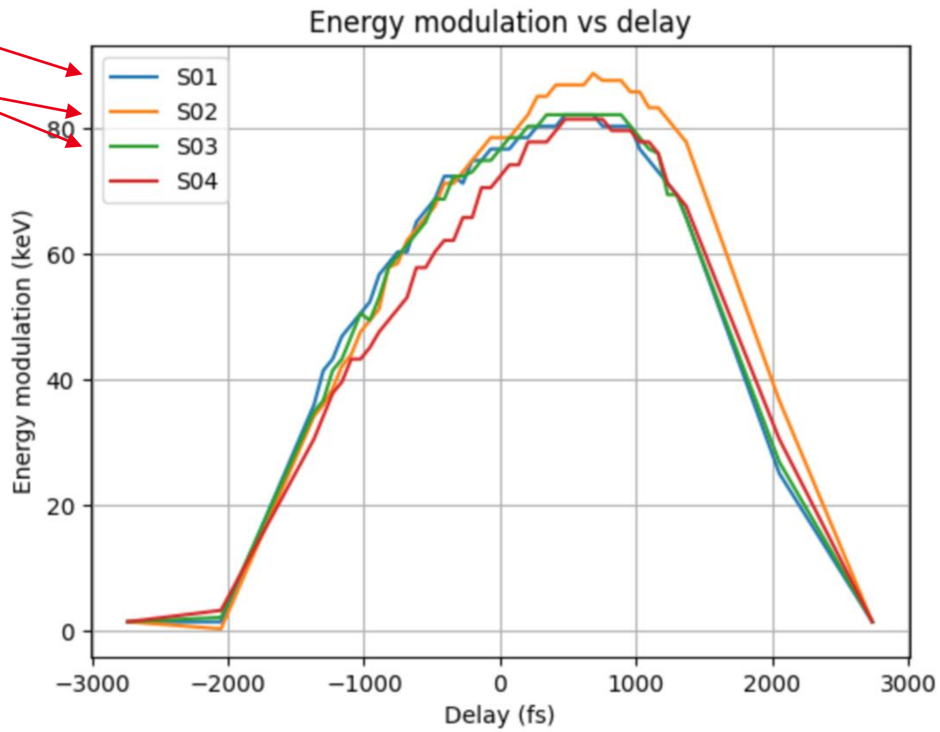
FIRST PULSE SHAPING MEASUREMENTS APPLYING AOPDF AT 2050NM



L. Genovese et al., CLEO, Munich, Germany (2025)

Electron beam dynamics simulations predict ~10% increase in energy gain

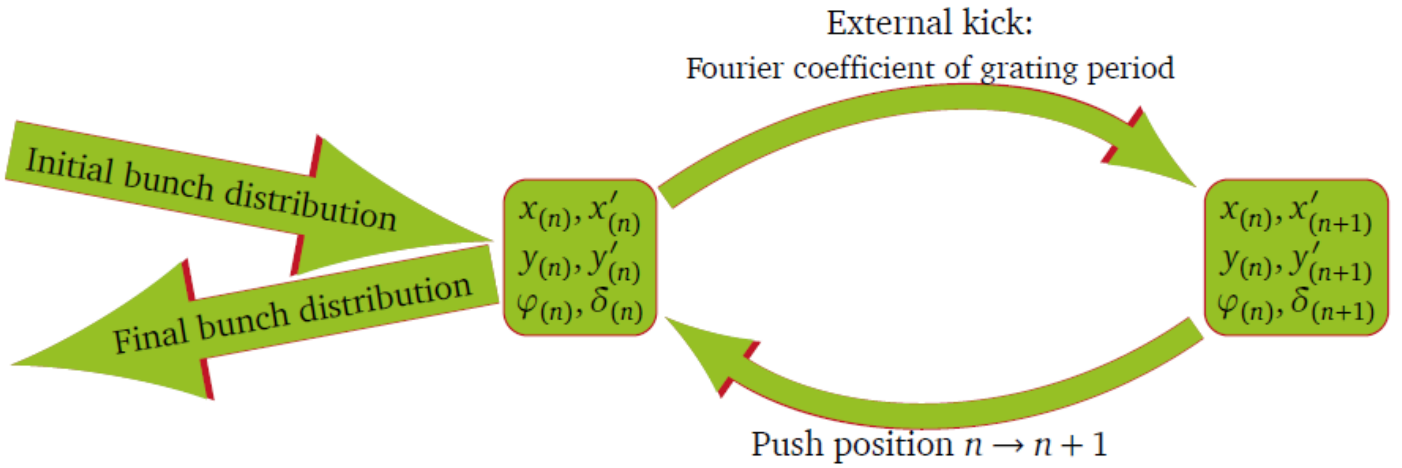


SIMULATION: DLATRACK6D

- Symplectic tracking code
- Kicks by $\underline{e}_1(x,y) = \underline{e}_1^0 \cosh\left(\frac{\omega y}{\beta\gamma c_0}\right)$
- Transverse kicks by Panofsky-Wenzel theorem

$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ \varphi \\ \delta \end{pmatrix}^{(n+1)} = \begin{pmatrix} x \\ Ax' + \Delta x'(x,y,\varphi) \\ y \\ Ay' + \Delta y'(x,y,\varphi) \\ \varphi \\ \delta + \Delta\delta(x,y,\varphi,\varphi_0) \end{pmatrix}^{(n)} + \begin{pmatrix} \lambda_z x'(x,y,\varphi) \\ 0 \\ \lambda_z y'(x,y,\varphi) \\ 0 \\ -\frac{2\pi}{\beta^2\gamma^2}\delta(x,y,\varphi) \\ 0 \end{pmatrix}^{(n+1)}$$

with $A^{(n)} = \frac{(\beta\gamma)^{(n+1)}}{(\beta\gamma)^{(n)}}$



- Python based
- Tracking parallelized on CPU
- Arbitrary laser pulse shape (pulse front tilt)
- Laser wavelength change during tracking (chirp)

U. Niedermayer, T. Egenolf, O. Boine-Frankenheim, Phys. Rev. Accel. Beams 20, 111302 (2017)

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DLA EXPERIMENT – INVERSE PROBLEM

Simulations

Initial electron bunch distribution
Laser pulse shape

Tracking

Final electron bunch distribution
(Energy spectrum)

Grating parameters

Experiments

Initial electron bunch distribution
Laser pulse shape

Reconstruction

Energy spectrum

Additional diagnostics
Grating parameters

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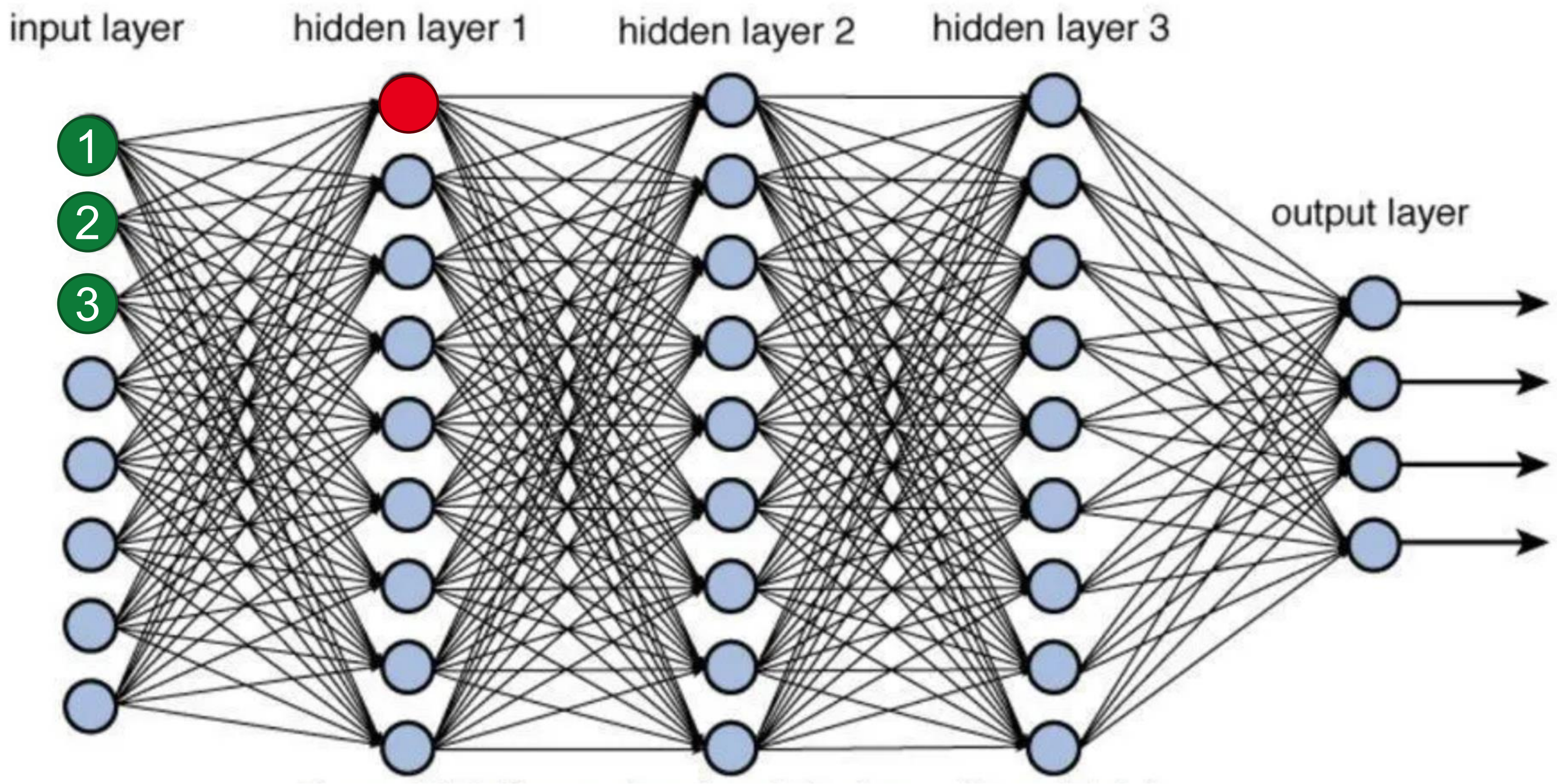
TEMF

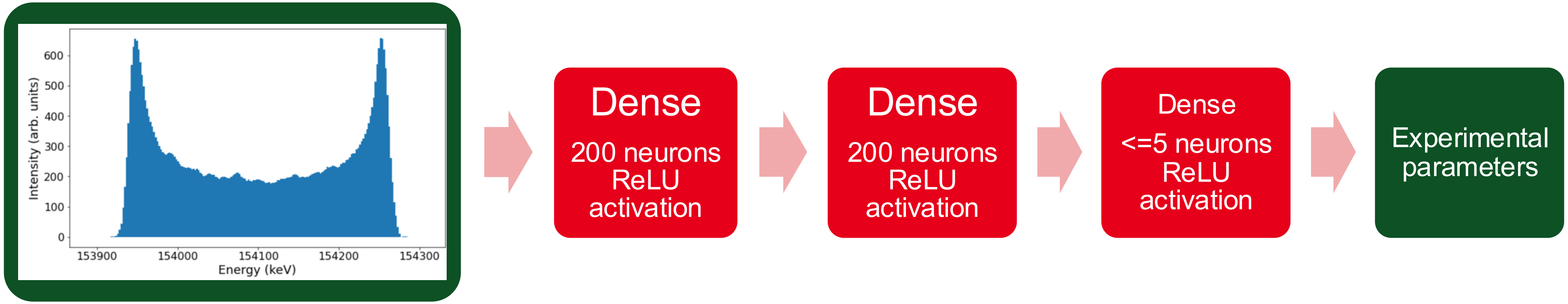
RECONSTRUCTION BY DEEP NEURAL NETS



$x = (x_1, x_2, \dots)$ ● $= w_1 *$ 1 $+ w_2 *$ 2 $+ w_3 *$ 3 $+ \cdots$ $y = (y_1, y_2, \dots)$

DESIGN OF THE NEURAL NETWORK

- Input: Binned energy spectrum of electrons after DLA interaction (~200 bins)
- Architecture
  - 3 layers fully connected (200 neurons → 200 neurons → <=5 neurons (till now)
  - ReLU activation function
  - Loss function: mean absolute error (parameters normalized→ percentage error)
- Output: Experimental parameters (input of tracking simulations)



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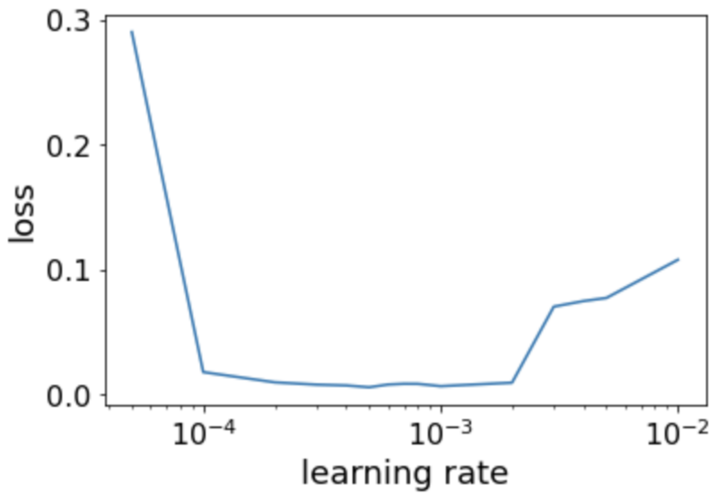
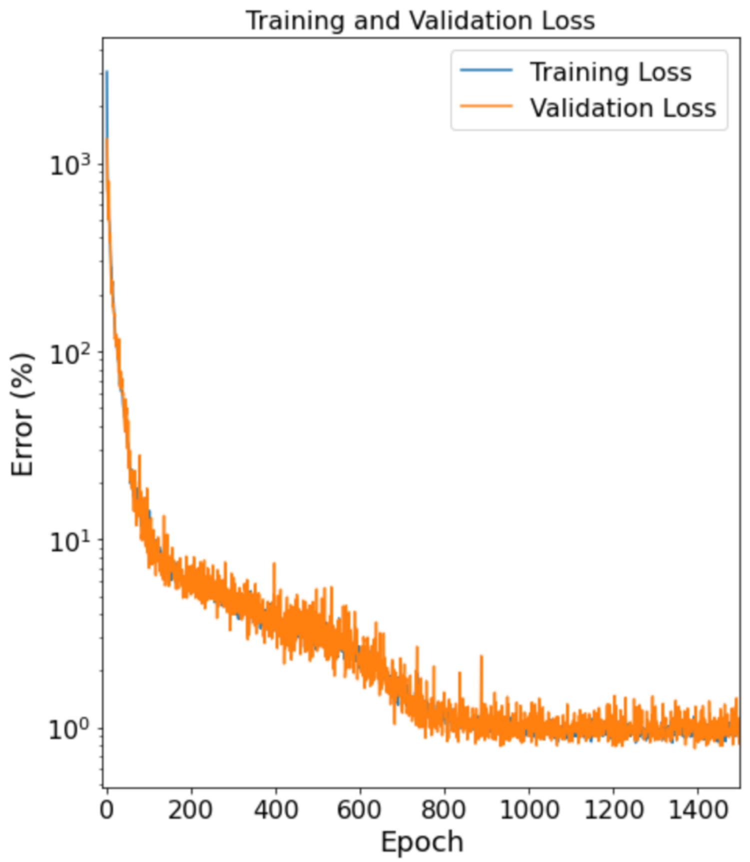
TRAINED NEURAL NET

- Implemented using pyTorch
- Trained with simulation data created by DLAtrack6D (~5000 simulations)
- Below 1% error in training and validation datasets





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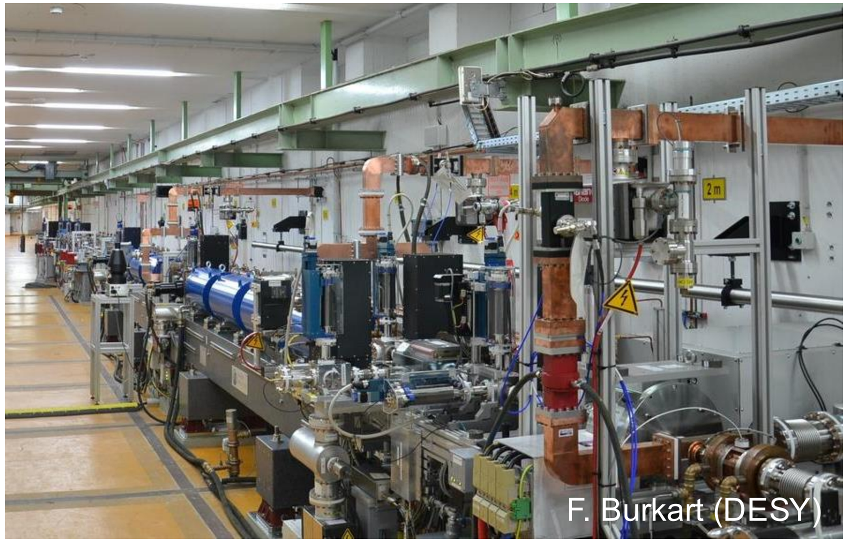
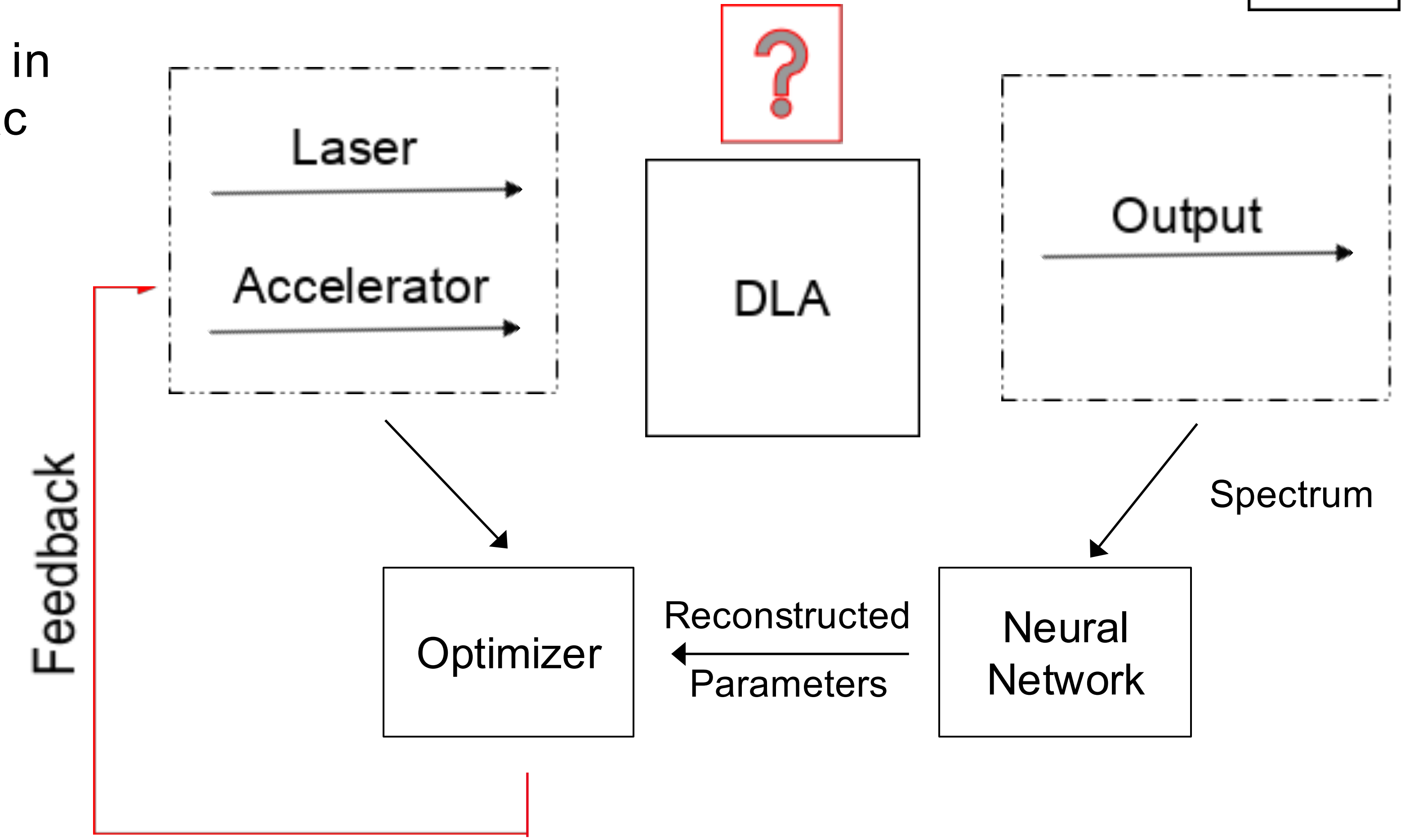
OUTLOOK: CONTROL AND OPTIMIZATION

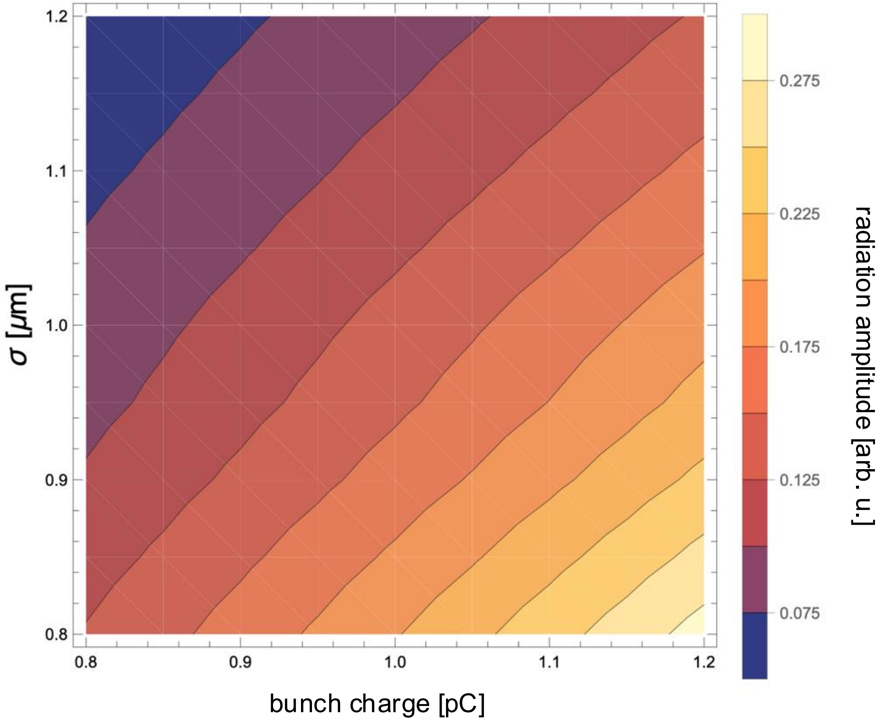
- Integration of surrogate model in control system of the R&D linac ARES at DESY

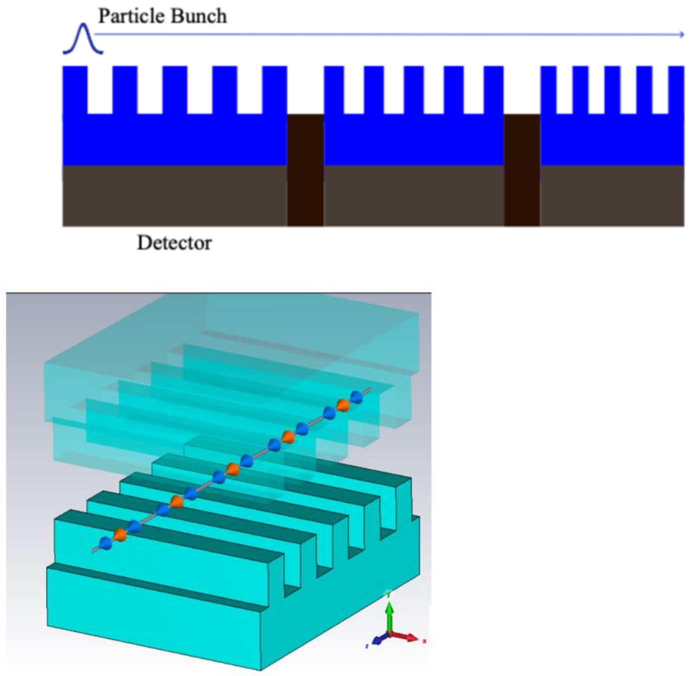

F. Burkart (DESY)



OUTLOOK: SMITH-PURCELL RADIATION DIAGNOSTICS

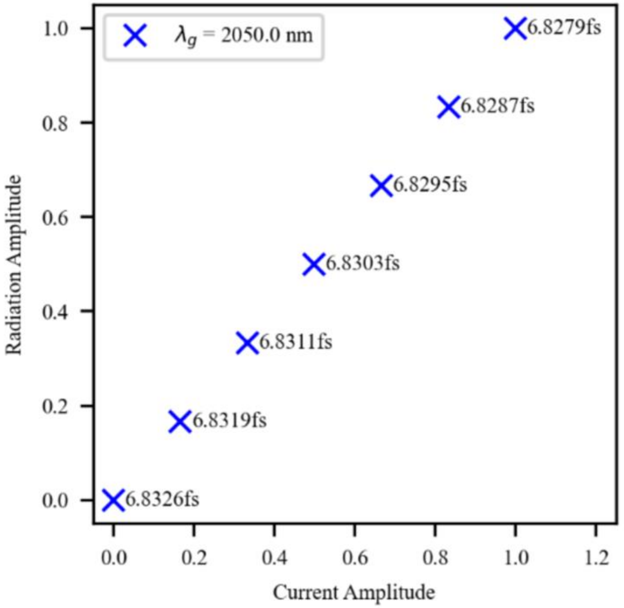
- Spectrum and radiation amplitude of cSPR depend on electron bunch properties
- Gratings for radiation generation could be integrated in a DLA design easily





R. Buhrmester (TU Darmstadt)

B. Stacey et al., J. Phys.: Conf. Ser. 2687, 072008 (2024)



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CONCLUSIONS

- Guiding and acceleration in DLA shown in theory and experiments
  - ➢ Electron accelerator
- Missing piece: diagnostics
  - ➢ At first required for laser pulse shape, but also for electrons
- Reconstruction with neural networks
  - ➢ Trained by simulation data (DLAtrack6D)
- Outlook: integration in control system and expansion to Smith-Purcell radiation

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