Accelerator on a chip: Recent results and perspectives for applications

6th European Advanced Accelerator Concepts workshop

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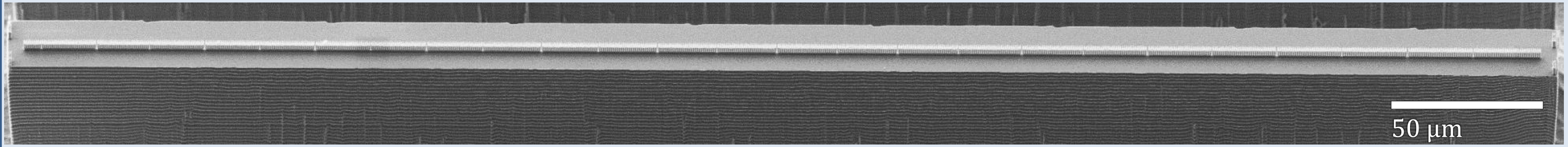

1962: First proposals

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Proposal for an Electron Accelerator Using an Optical Maser

Koichi Shimoda

January 1962 / Vol. 1, No. 1 / APPLIED OPTICS 33

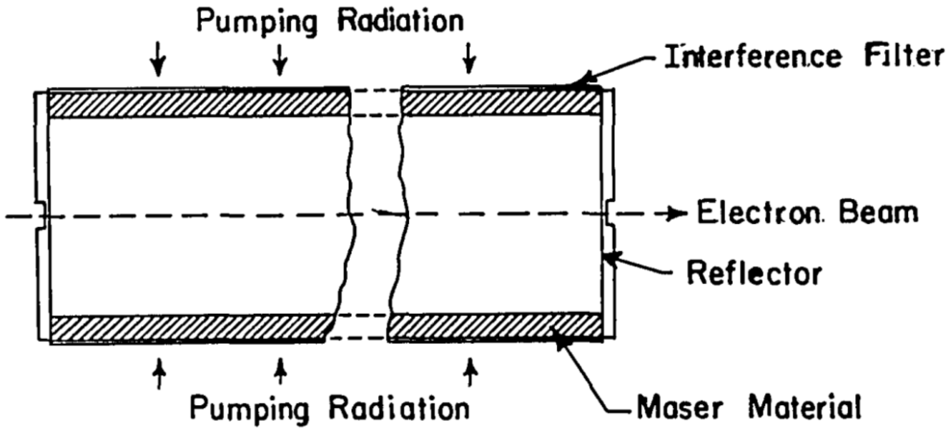


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

IBM TN-5

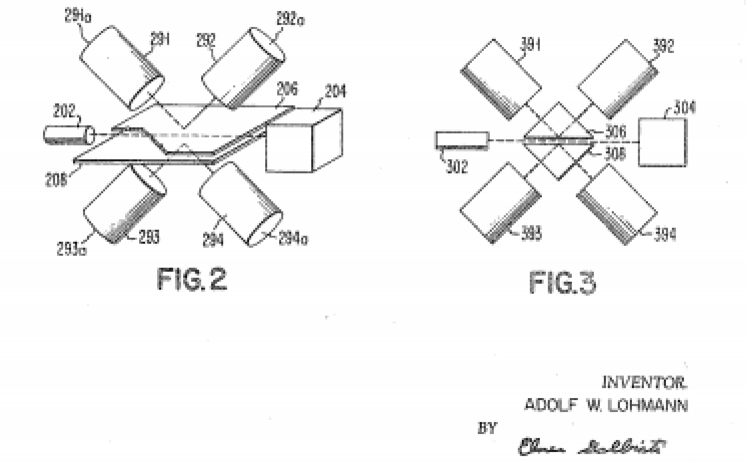
Electron Acceleration by Light Waves

A. Lohmann*

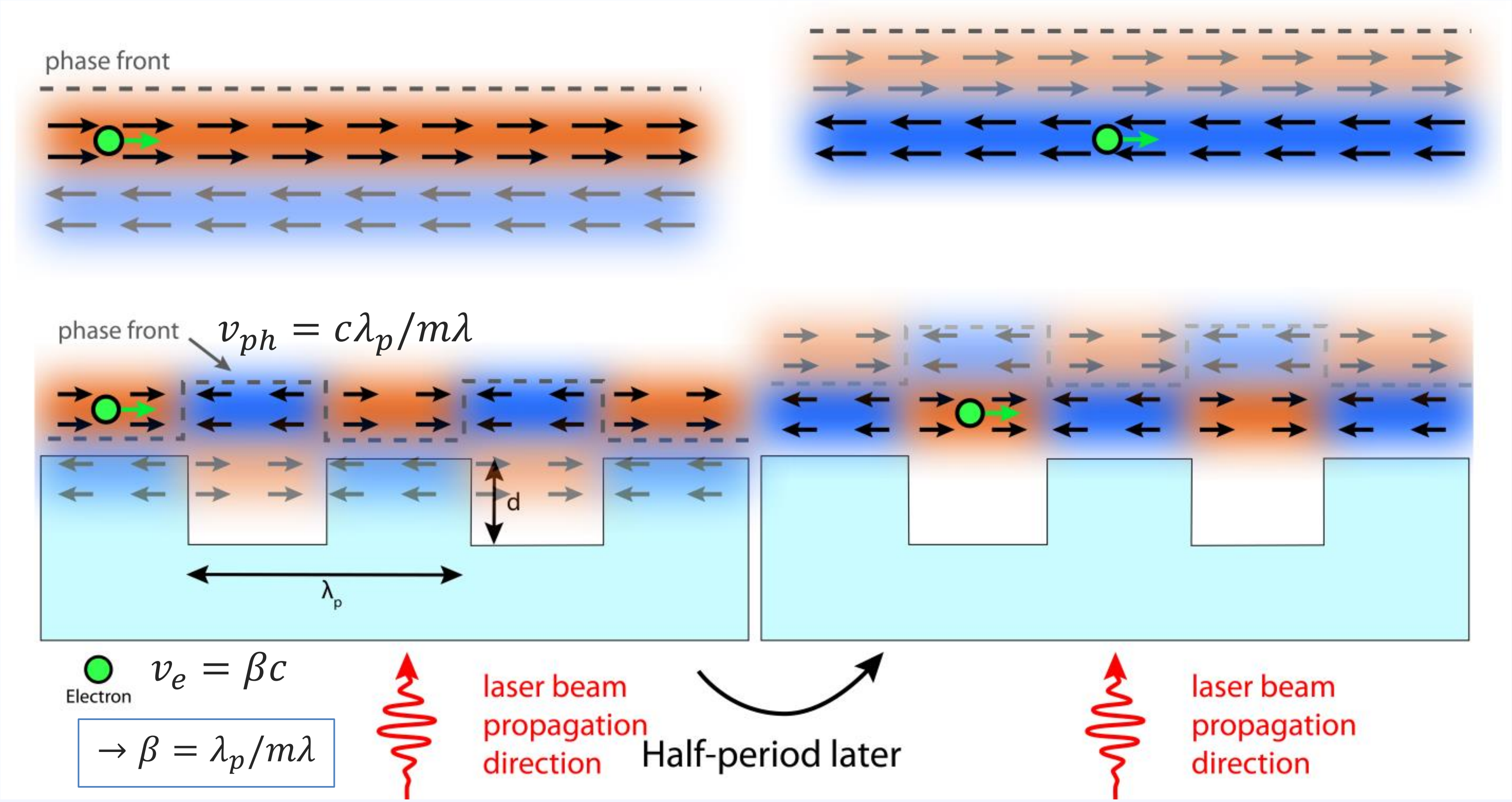
October 3, 1962

3,267,383
PARTICLE ACCELERATOR UTILIZING COHERENT LIGHT
Adolf W. Lohmann, San Jose, Calif., assignor to International Business Machines Corporation, New York, N.Y., a corporation of New York
Filed May 27, 1963, Ser. No. 283,475
9 Claims. (Cl. 328—33)

The present invention relates to particle accelerators and more particularly to a particle accelerator wherein energy is transferred to particles by means of visible or infrared light waves.

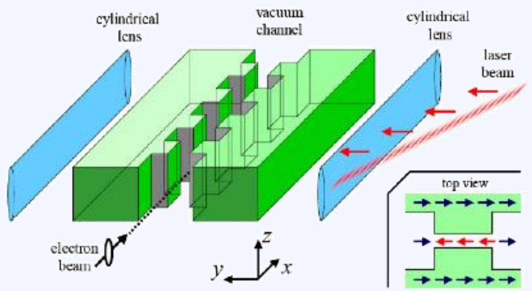


Phase synchronous acceleration: matching electrons to photons

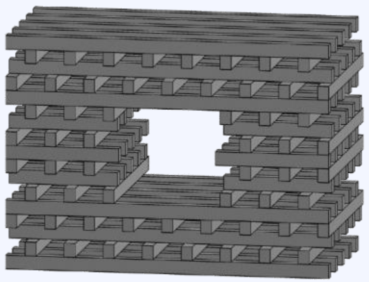


Synchronicity/Widerøe condition

A family of nanophotonic structures



Plettner, Lu, Byer, Phys. Rev. ST AB **9**, 111301 (2006)



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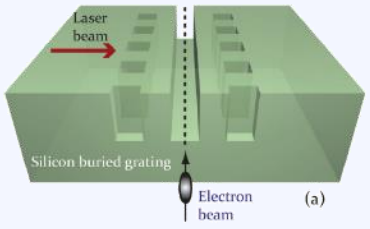
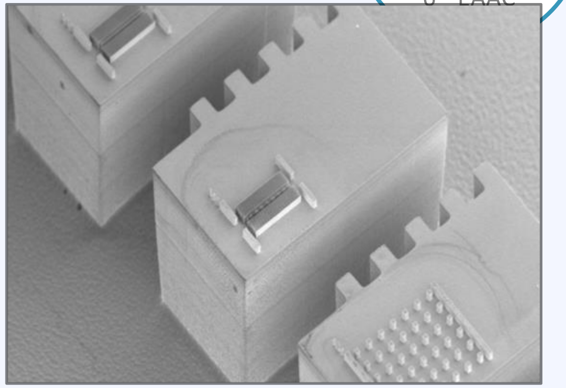
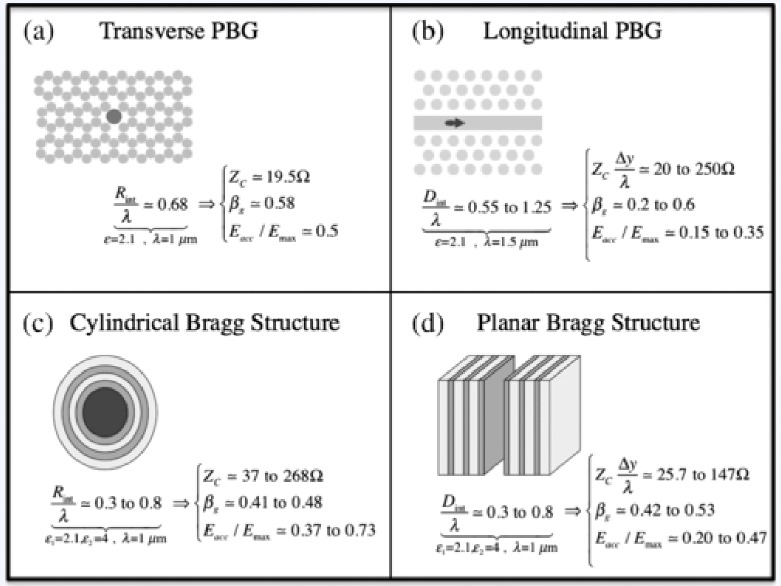
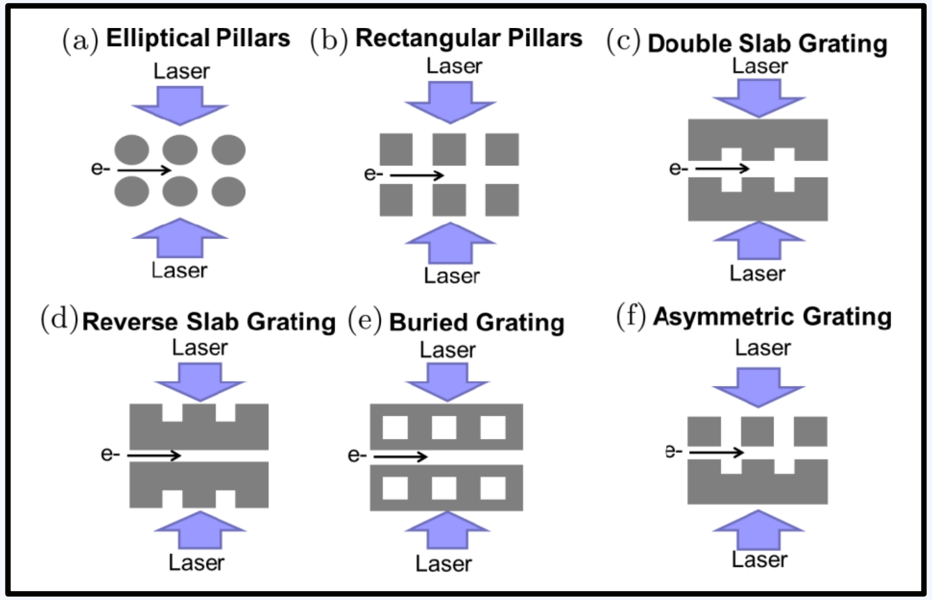


Chang, Solgaard, APL **104**, 184102 (2014)

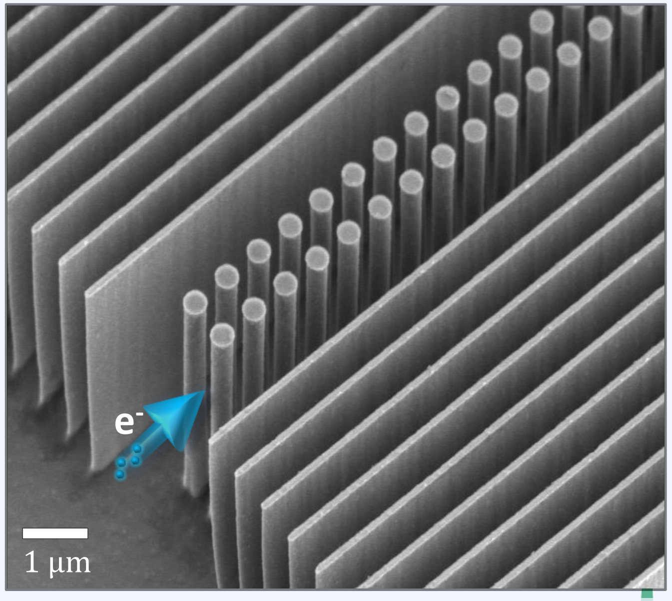




REVIEW: England et al., "Dielectric laser accelerators," Rev. Mod. Phys. **86**, 1337 (2014)



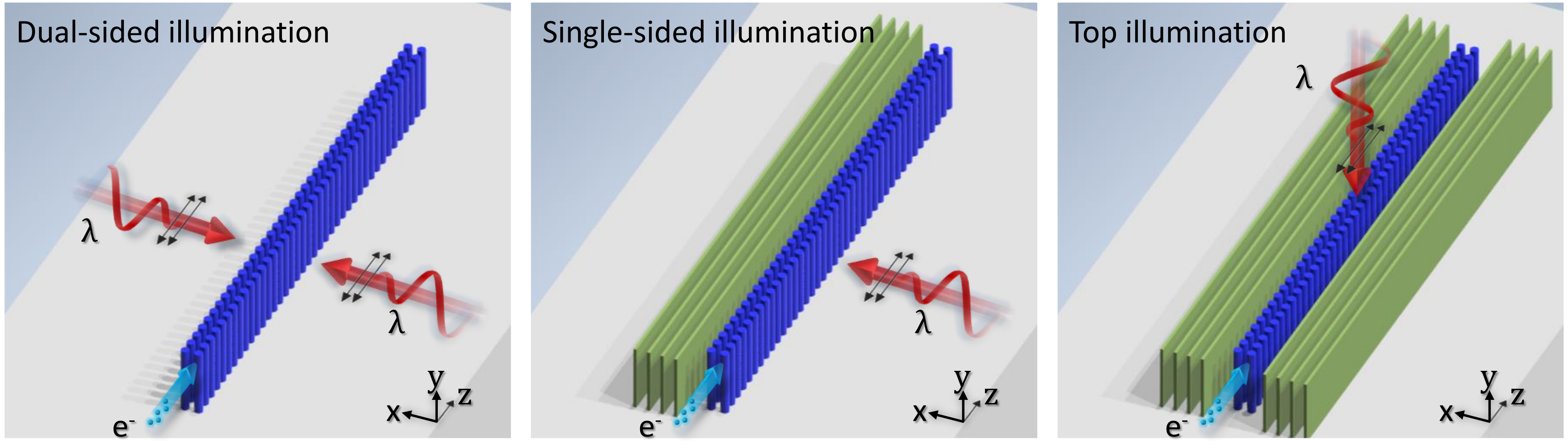
REVIEW: Wootton, McNeur, Leedle, "Dielectric Laser Accelerators: Designs, Experiments, and Applications," Rev. of Accel. Sci. and Tech. **9**, 105-126 (2016)

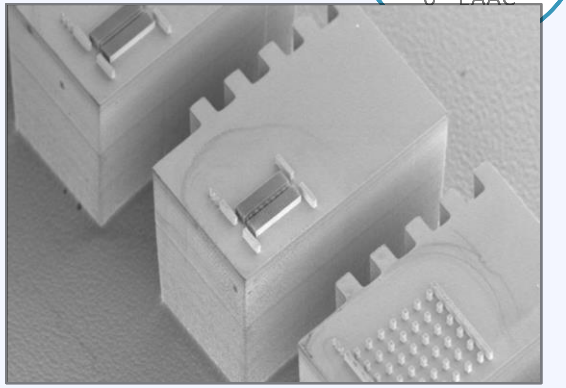


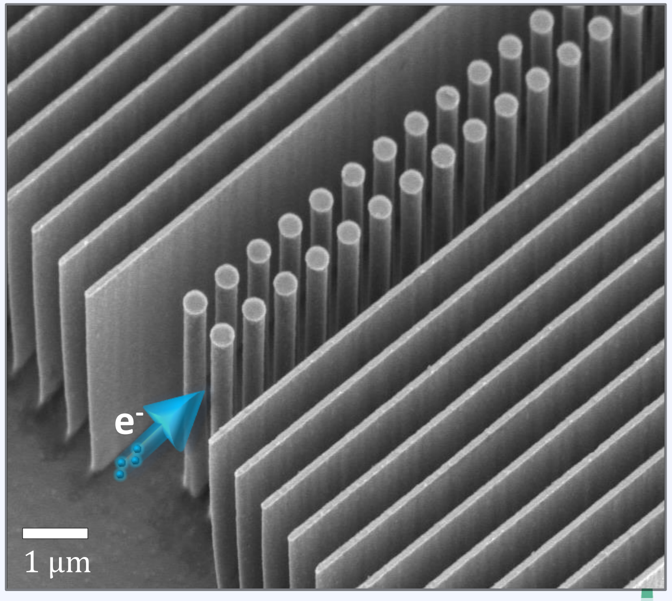
Shiloh et al., Opt. Exp. **29**, 14403 (2021)

REVIEW: Shiloh et al., "Miniature light-driven nanophotonic electron acceleration and control", Adv. Opt. Photon. **14**, 862-932 (2022)

Driving the dual-pillar nanophotonic accelerator







Shiloh et al., Opt. Exp. **29**, 14403 (2021)

„Dual pillar" structure:

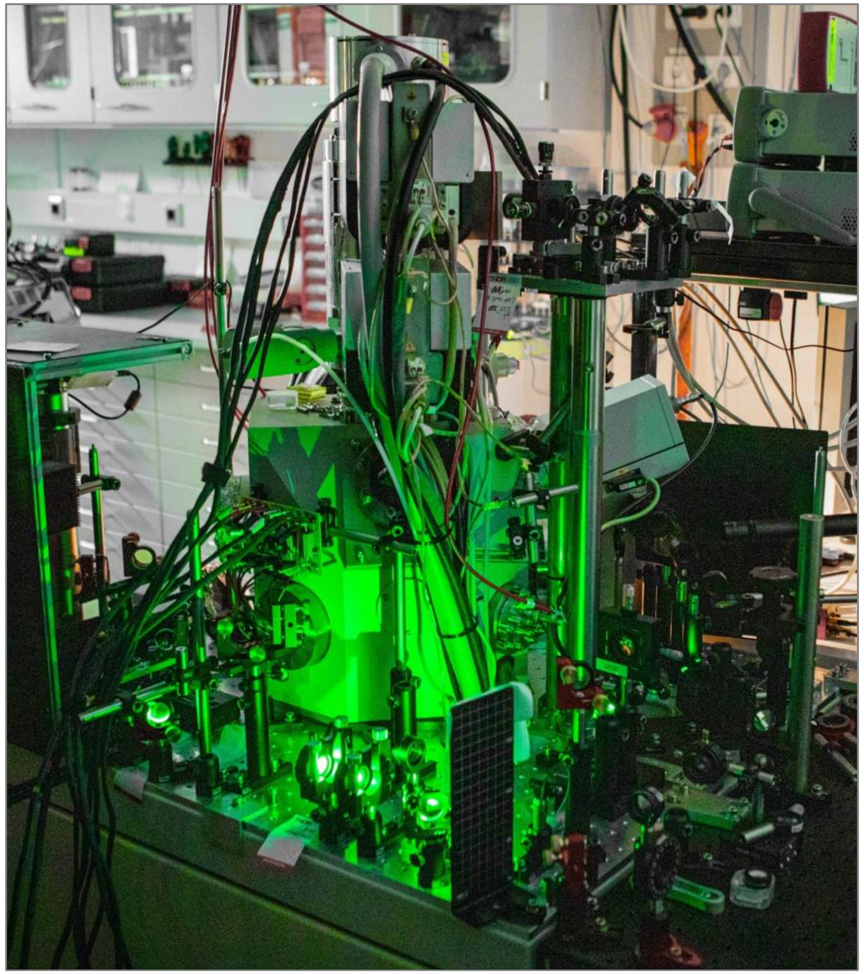
- ✓ Simple fabrication process (e-beam lithography + etching)
- ✓ Can fabricate thousands of accelerators per day in a University clean room
- ✓ No nonlinear optical effects (laser doesn't traverse the bulk)
- ✓ Operates with evanescent near-fields; NOT a cavity (no loading time)

REVIEW: Shiloh et al., "Miniature light-driven nanophotonic electron acceleration and control", Adv. Opt. Photon. **14**, 862-932 (2022)

Driving the dual-pillar nanophotonic accelerator

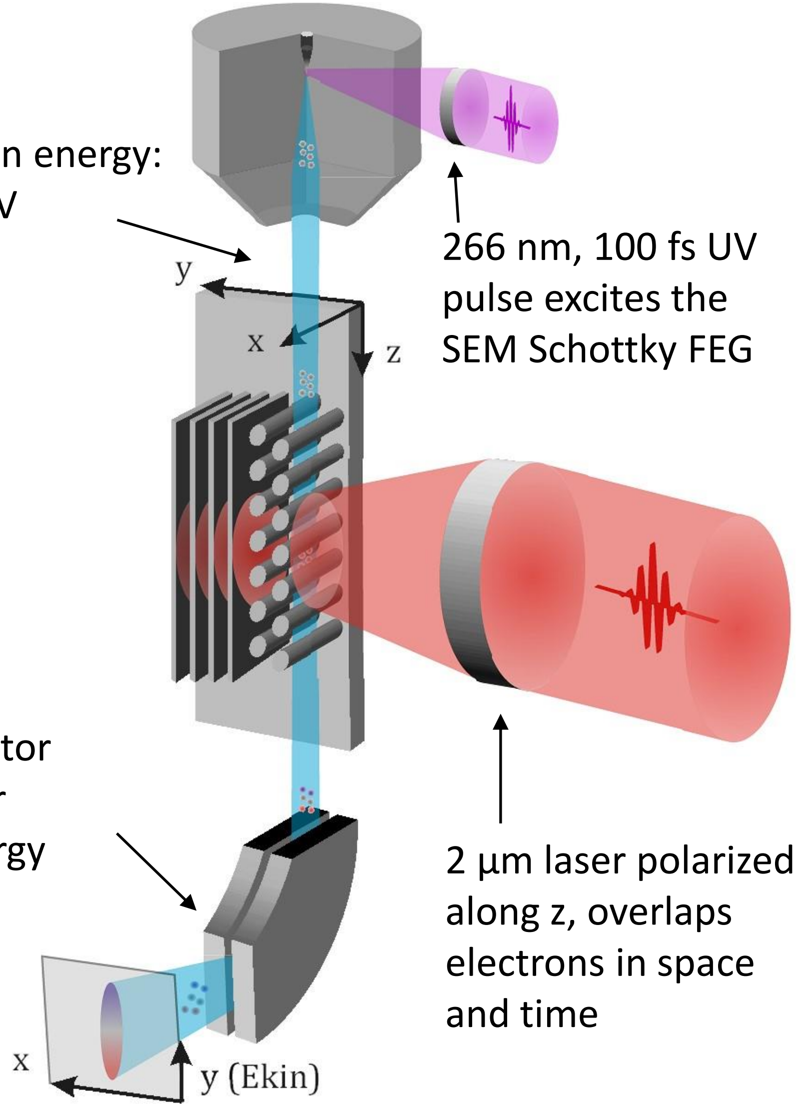
Our femtosecond laser parameters:

Wavelength	1.93 µm
Pulse duration	250 fs
Laser power	10 W
Repetition rate	167 kHz
Pulse energy	60 µJ
Wall-plug efficiency	>30%

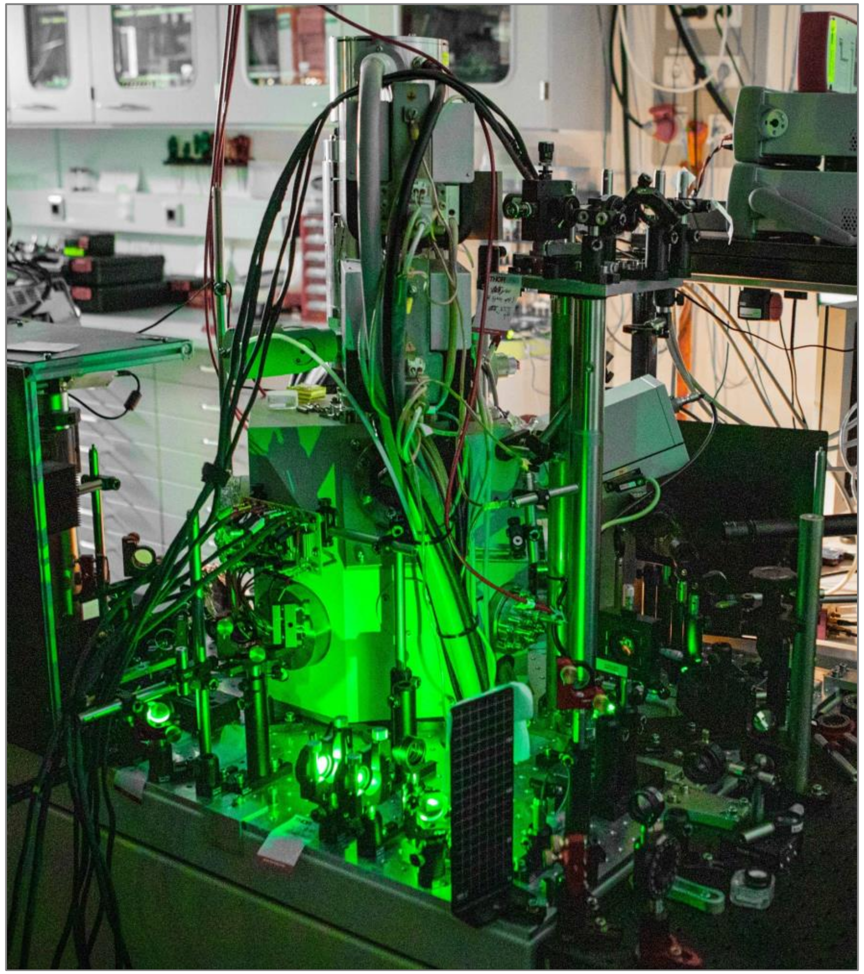


The ultrafast scanning electron microscope @ FAU Erlangen

Driving the dual-pillar nanophotonic accelerator (with keV energies)



Yousefi et al., Opt. Lett. **44**, 6 (2019)



The ultrafast scanning electron microscope @ FAU Erlangen

ACHIP: Accelerator on a Chip International Program (2015-2023)

Organizational chart

PIs: R. L. Byer, Stanford, P. Hommelhoff, FAU Erlangen

Sub-Relativistic DLA experiments
Stanford: Harris, Solgaard
Erlangen: Hommelhoff

Structures
Stanford: Harris, Solgaard, Byer
Erlangen: Hommelhoff

System integration (Core DLA groups)
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Electron source
UCLA: Musumeci
Erlangen: Hommelhoff
Stanford: Harris, Solgaard

Simulations
U Darmstadt: Boine-Frankenheim

Light Coupling
Stanford: Fan, Vučković

Associated Scientific Collaborators
Yenchieh Huang (Tsinghua)
Zhirong Huang (SLAC)
Kazu Koyama (Tokyo U)
Ido Kaminer (Technion)
James Rosenzweig (UCLA)
Evgenya Simakov (Los Alamos)

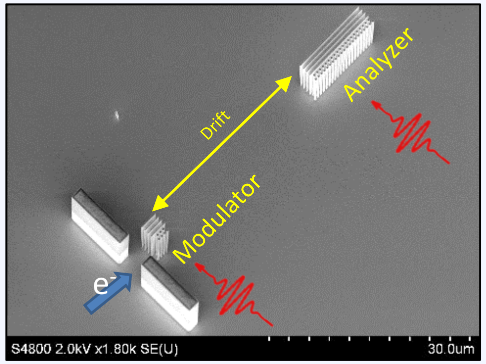
Relativistic DLA experiments
SLAC: England, Tantawi
DESY/UnivHH: Aßmann, Kärtner, Hartl
PSI/EPFL: Ischebeck, Rivkin

Industrial affiliate
HAMAMATSU
PHOTON IS OUR BUSINESS
(joined June 2017)

Sept. 2015 – March. 2023

ACHIP Scientific Advisory Board:
Ady Arie, Tel Aviv; Reinhard Brinkmann, DESY; Tor Raubenheimer, SLAC
Former members: Chan Joshi, UCLA, Lia Merminga, SLAC

ACHIP: Accelerator on a Chip International Program (2015-2023)



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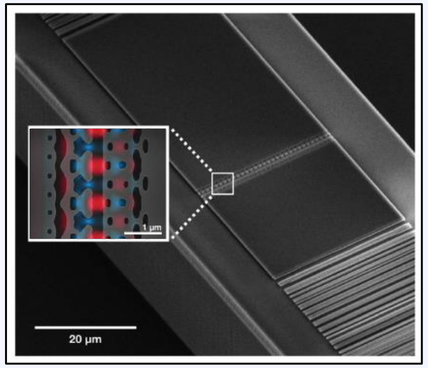
Black et al., Phys. Rev. Lett. **123**, 264802 (2019)



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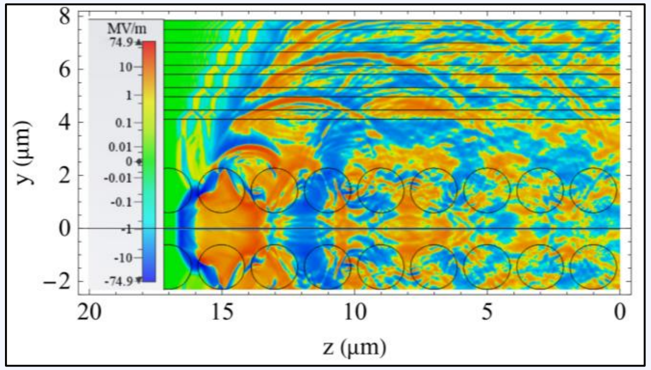

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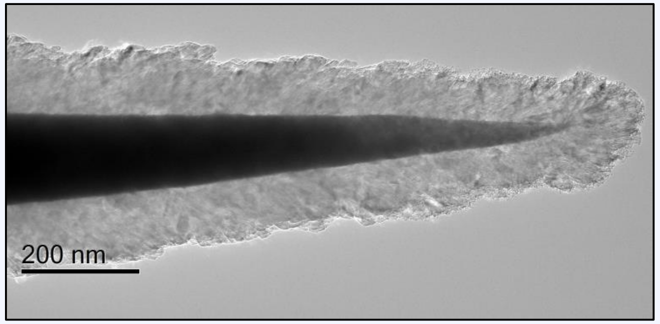

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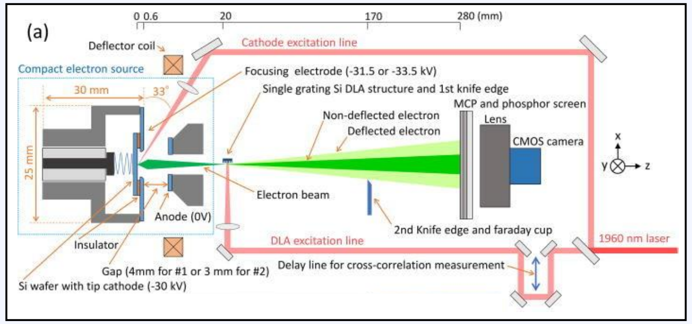

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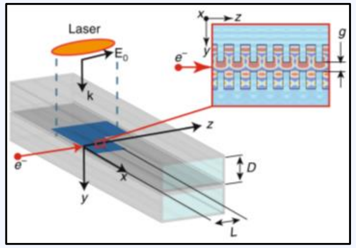

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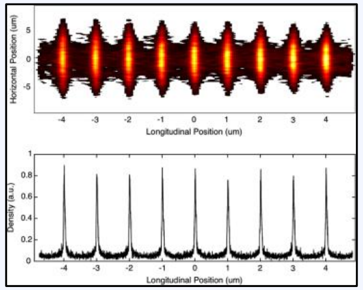

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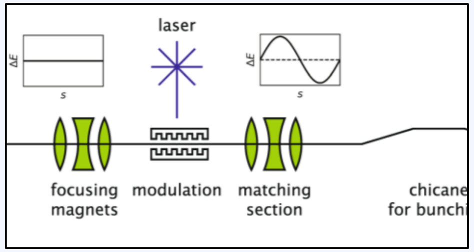

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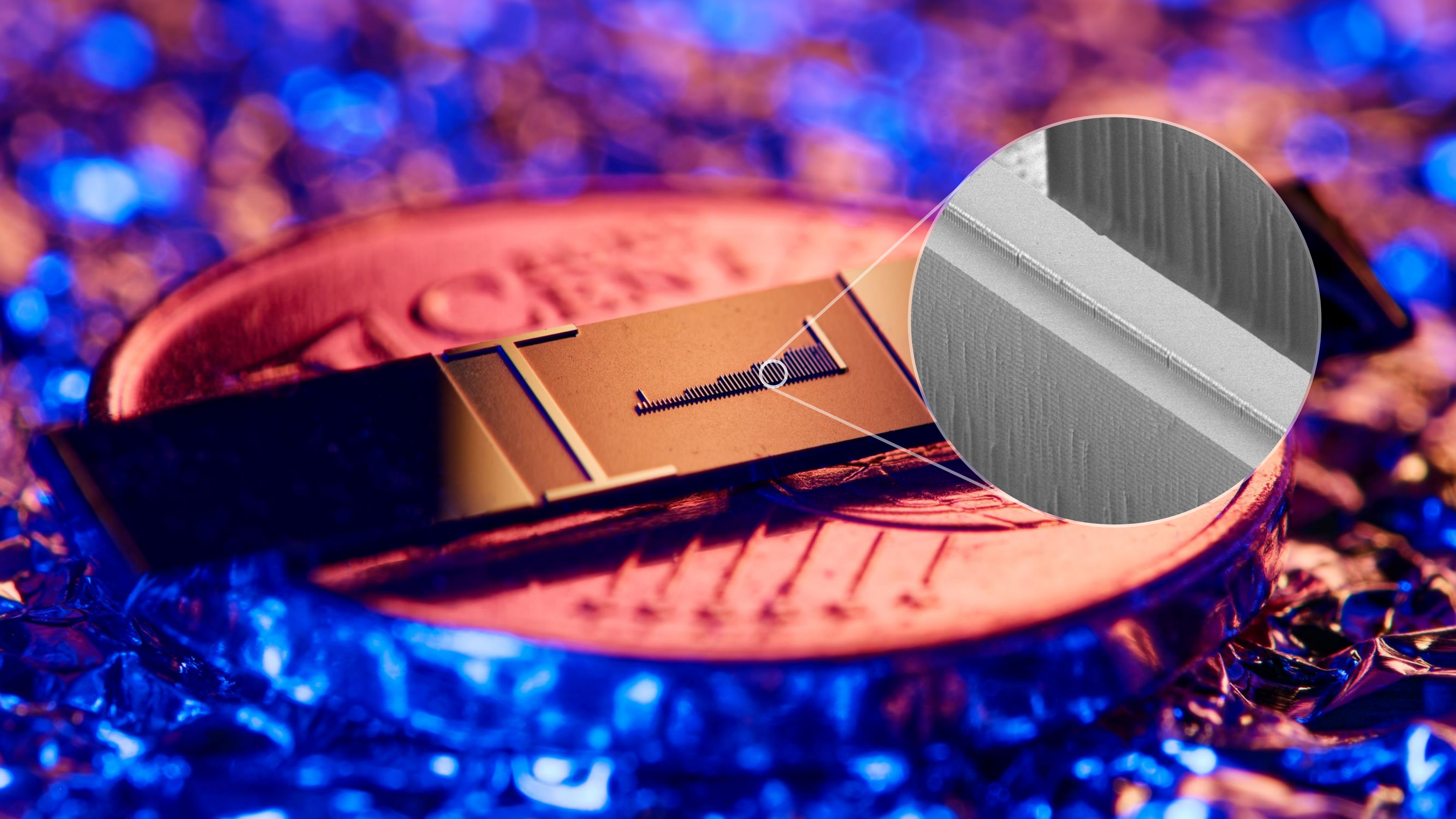
*As presented in EAAC 2021



Dielectric Laser Acceleration - DLA

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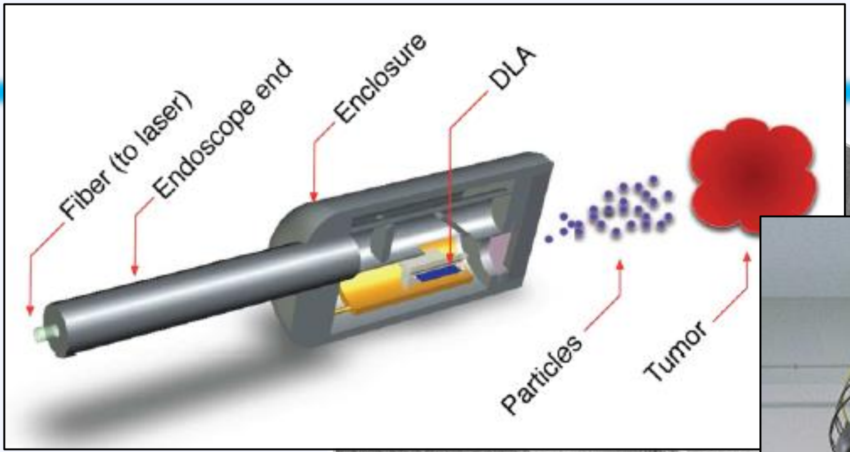
2023

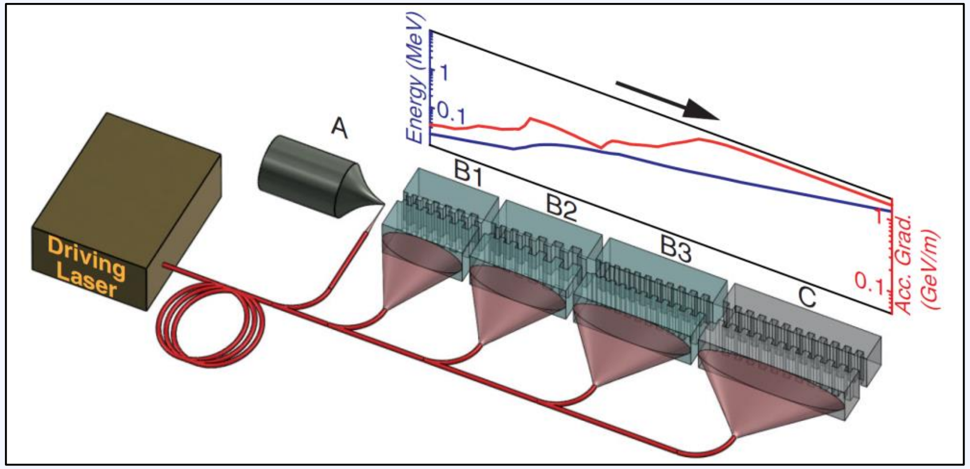
Opportunities?

- Novel solution in minimally-invasive medical treatment
- Tabletop high energy pulsed electron source
- University lab-run tunable light source
- Attosecond electron pulses at laser repetition rate
- Single electron wavepackets + single photons: quantum science



England et al., Rev. Mod. Phys. **86**, 1337 (2014)

3 MV electron microscope
(Hitachi - Osaka University)



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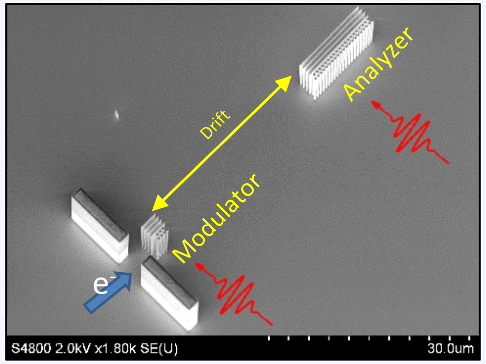
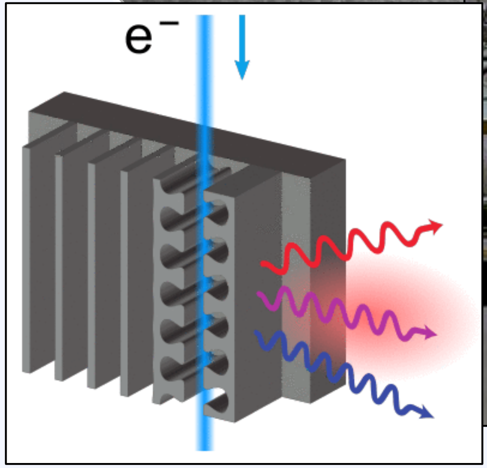


Schönenberger et al., Phys. Rev. Lett. **123**, 264803 (2019)
Black et al., Phys. Rev. Lett. **123**, 264802 (2019)



Häusler et al., *ACS Photonics* **9** (2022)

DLA is easily applicable with high injection energies..

DLA is easily applicable with high injection energies..

SINBAD

@ ARES

DESY.

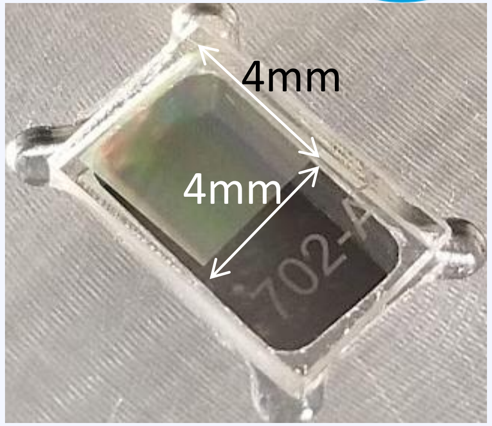
PRELIMINARY RESULTS

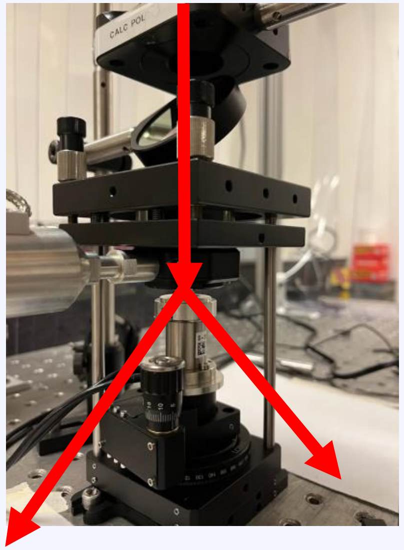
See talk by Sophie Crisp TUE 16:45 WG4

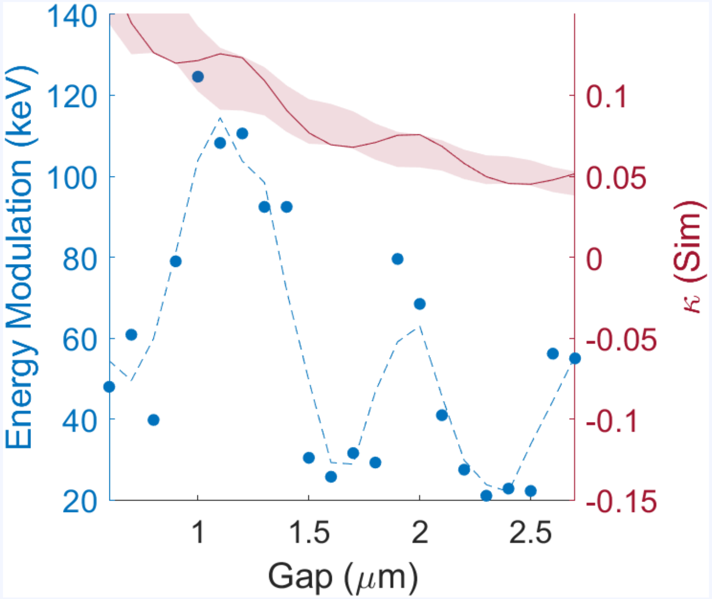
DLA is easily applicable with high injection energies..

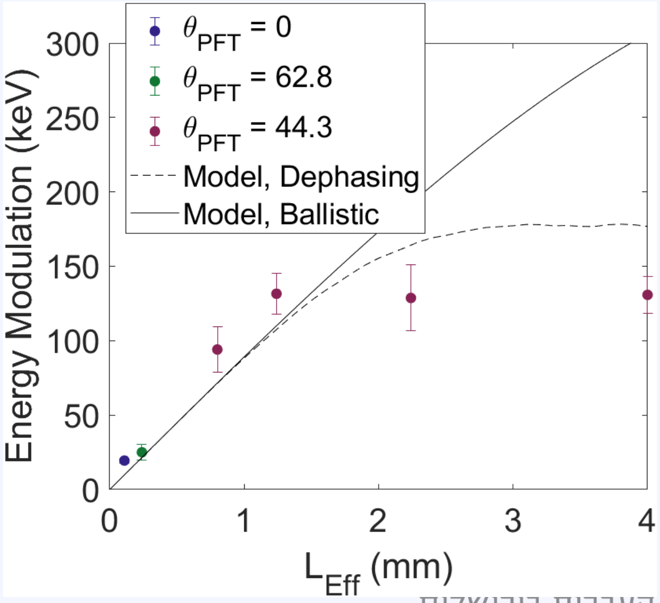
Extended Interaction Length in a Tunable Dielectric Laser Accelerator

- **6 MeV** beams from the Pegasus facility
- Demonstrated nm-scale tunable structures
  - Constructed from commercially obtained gratings
  - Optical diagnostic allows for out of vacuum structure building
- Piezo mounting allows for in-situ tuning for maximal modulation
- Up to 1.24 mm interactions increase energy modulation, then dephasing limits modulation









Paper in progress: S. Crisp, A. Ody, R.J. England, P. Musumeci

See talk by Rasmus Ischebeck TUE 17:25 WG4

DLA is easily applicable with high injection energies..

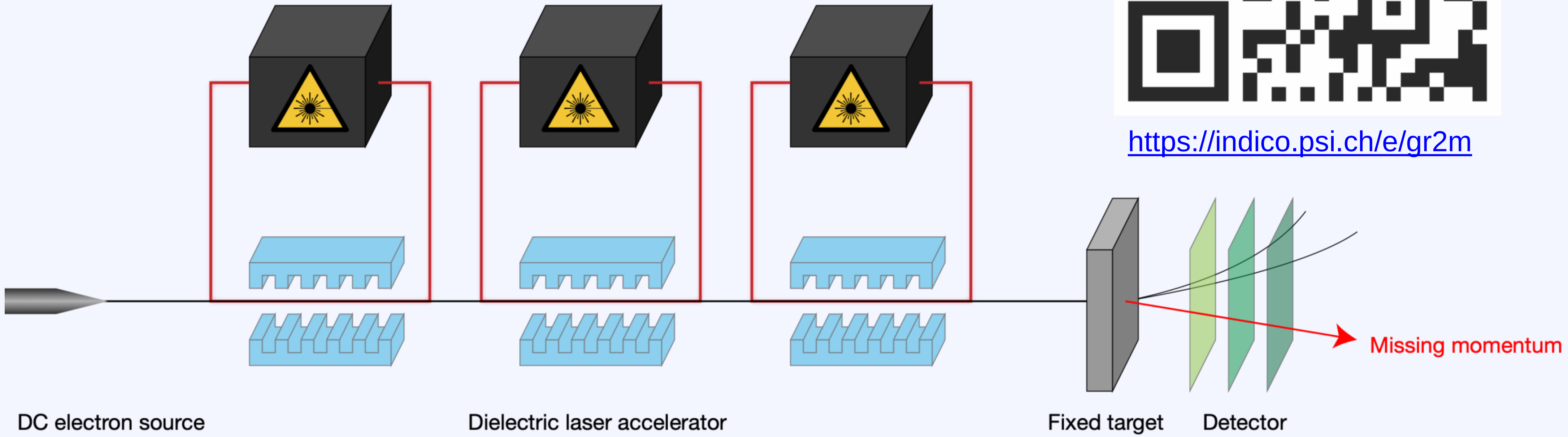
Single Electron Accelerator for Dark Matter Search

Concept:

- Generation of single electrons with a DC source
- Acceleration to 20 GeV in DLA
- Fixed-target experiment with a clean initial state
- Search for missing momentum and energy

- Workshop

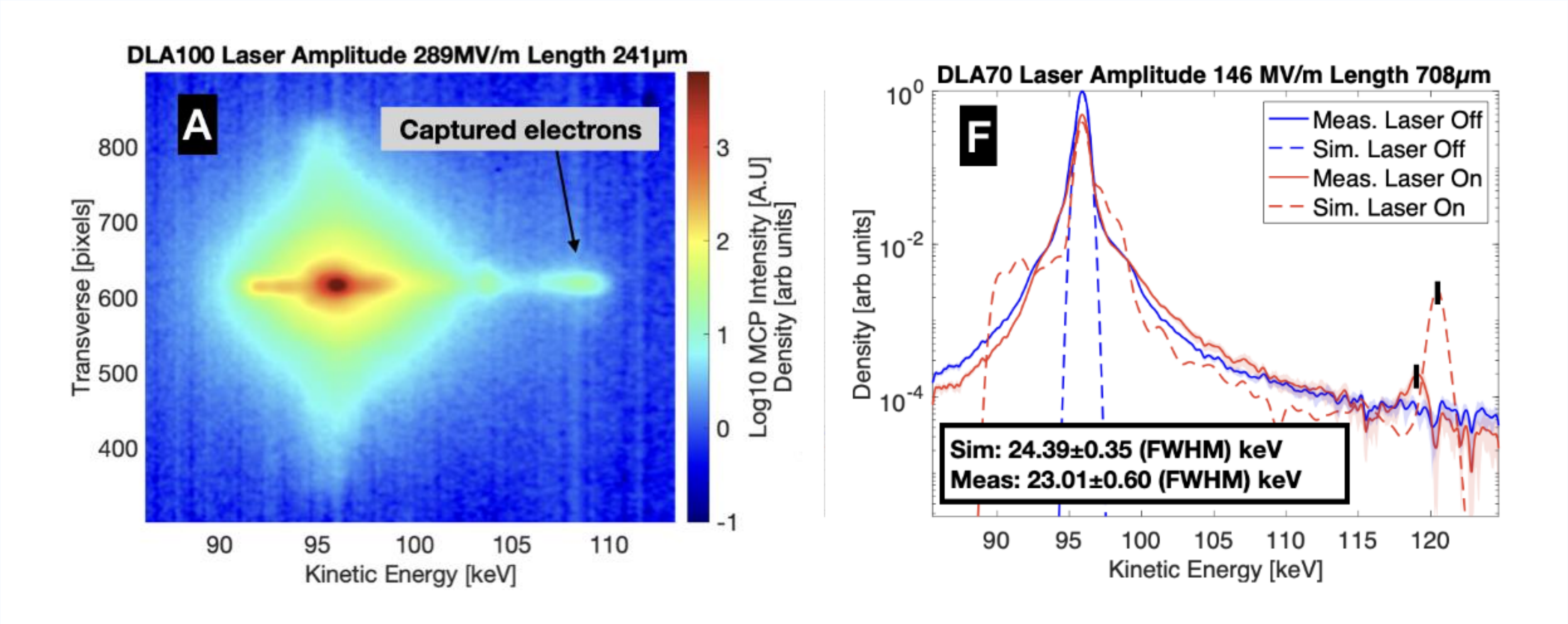
https://indico.psi.ch/e/gr2m



Rasmus Ischebeck, Raziyeh Dadashi, Massimilano Ferro-Luzzi, Richard Jacobsson, Witek Krasny, Mike Seidel, Frank Zimmermann

..But we experiment at keV injection energies

-> 25% increase from 96 keV injection energy



Broaddus, Egenolf, Black, Murillo, Woodahl, Miao, Niedermayer, Byer, Solgaard, “Sub-relativistic Alternating Phase Focusing Dielectric Laser Accelerators”, **in review** (2023)

-> Similar results from us in Erlangen – See talk by Tomáš Chlouba TUE 17:05 WG4

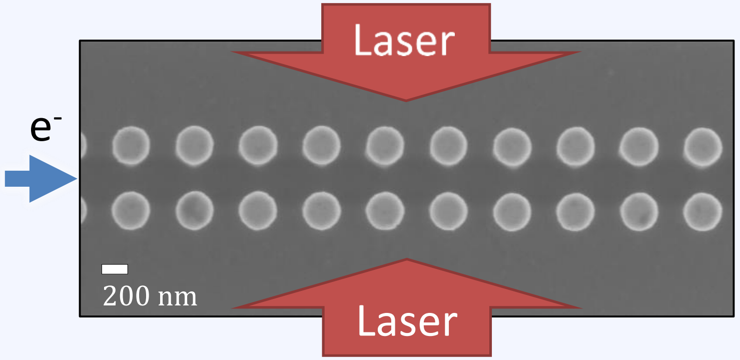
Challenges at keV injection energies

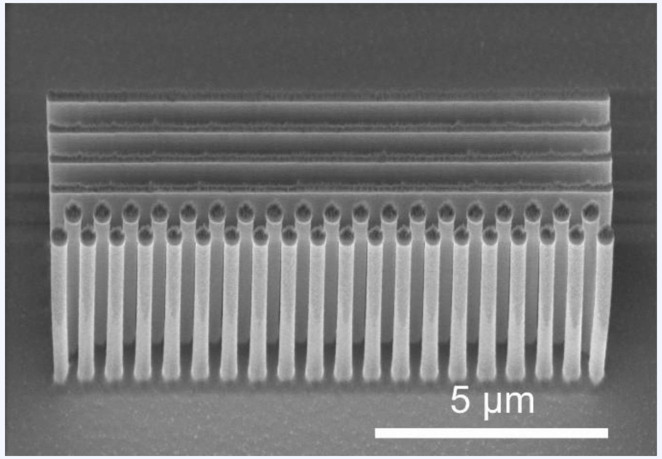
roy.shiloh@mail.huji.ac.il

Challenges at keV injection energies

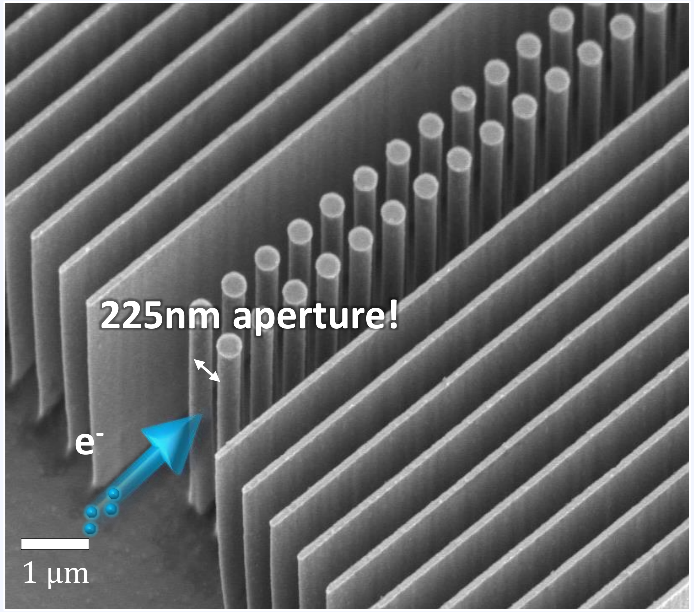
<u>Structure fabrication</u>: tolerances mainly depend on laser wavelength and electron energy

$$\beta = \lambda_p / m\lambda$$

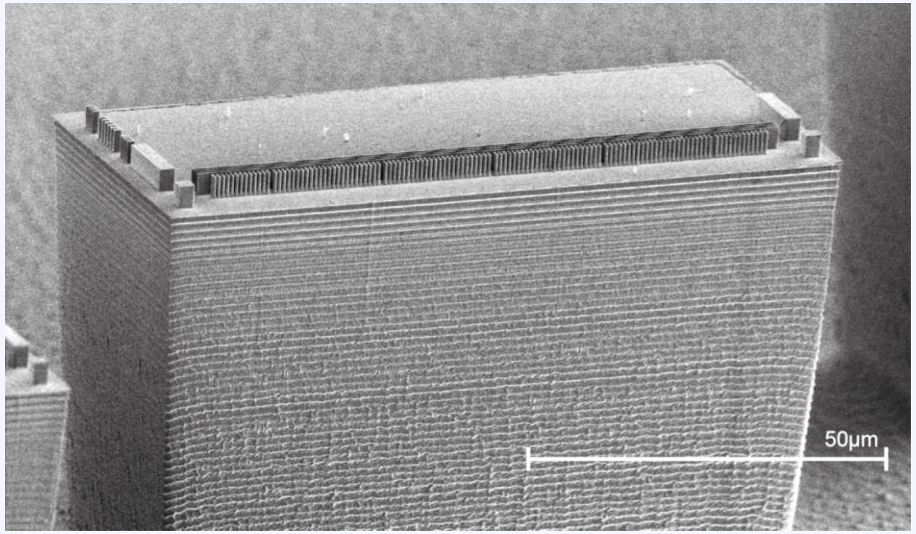




Yousefi et al., NIMA **909**, 221 (2018)



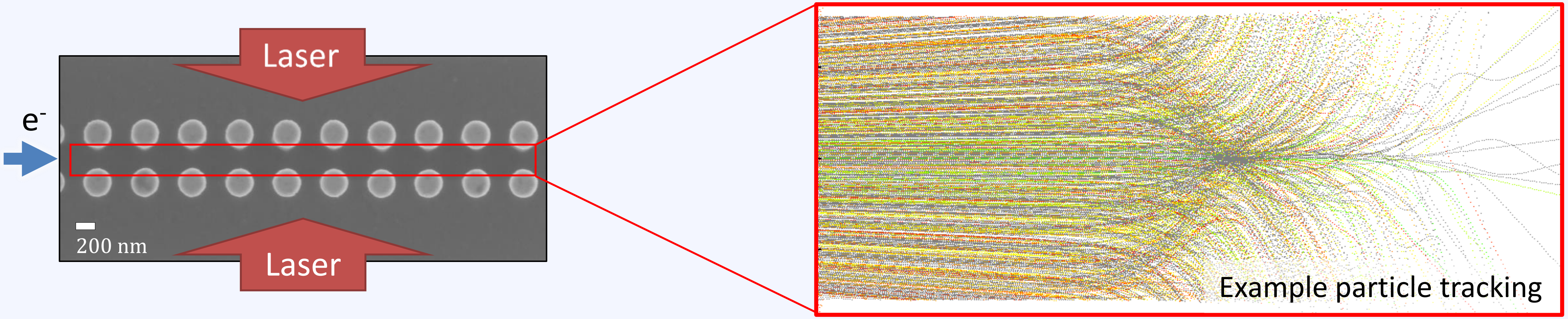
Shiloh, Chlouba, Yousefi, Hommelhoff
Opt. Exp. **29**, 14403 (2021)

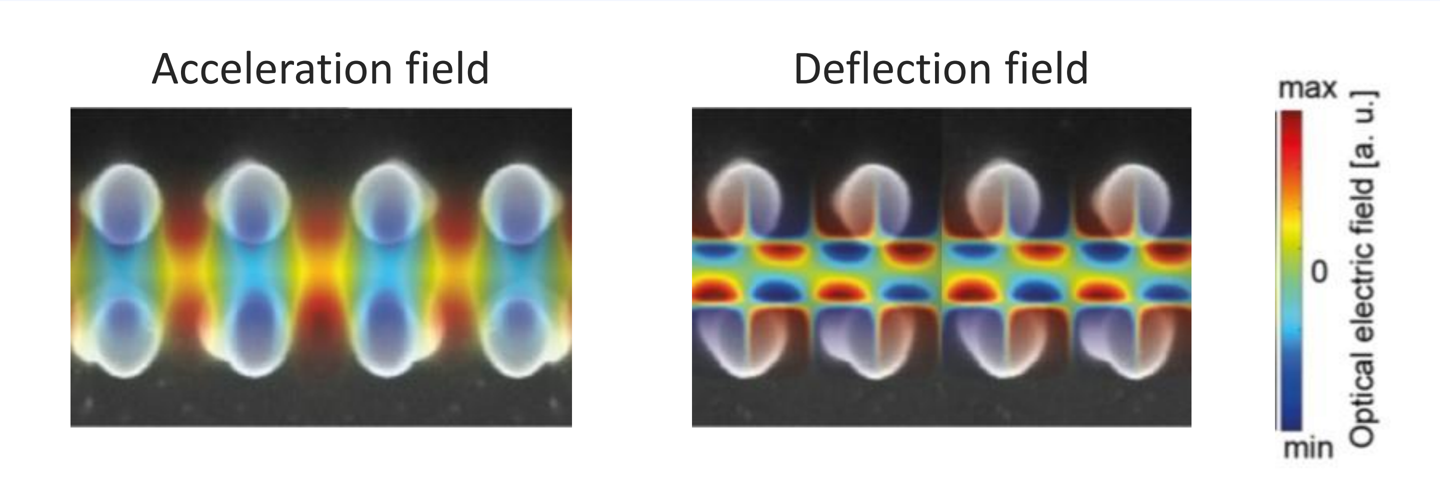


Shiloh*, Illmer*, Chlouba*, et. al., *Nature* **597**, 498-502 (2021)

Challenges at keV injection energies

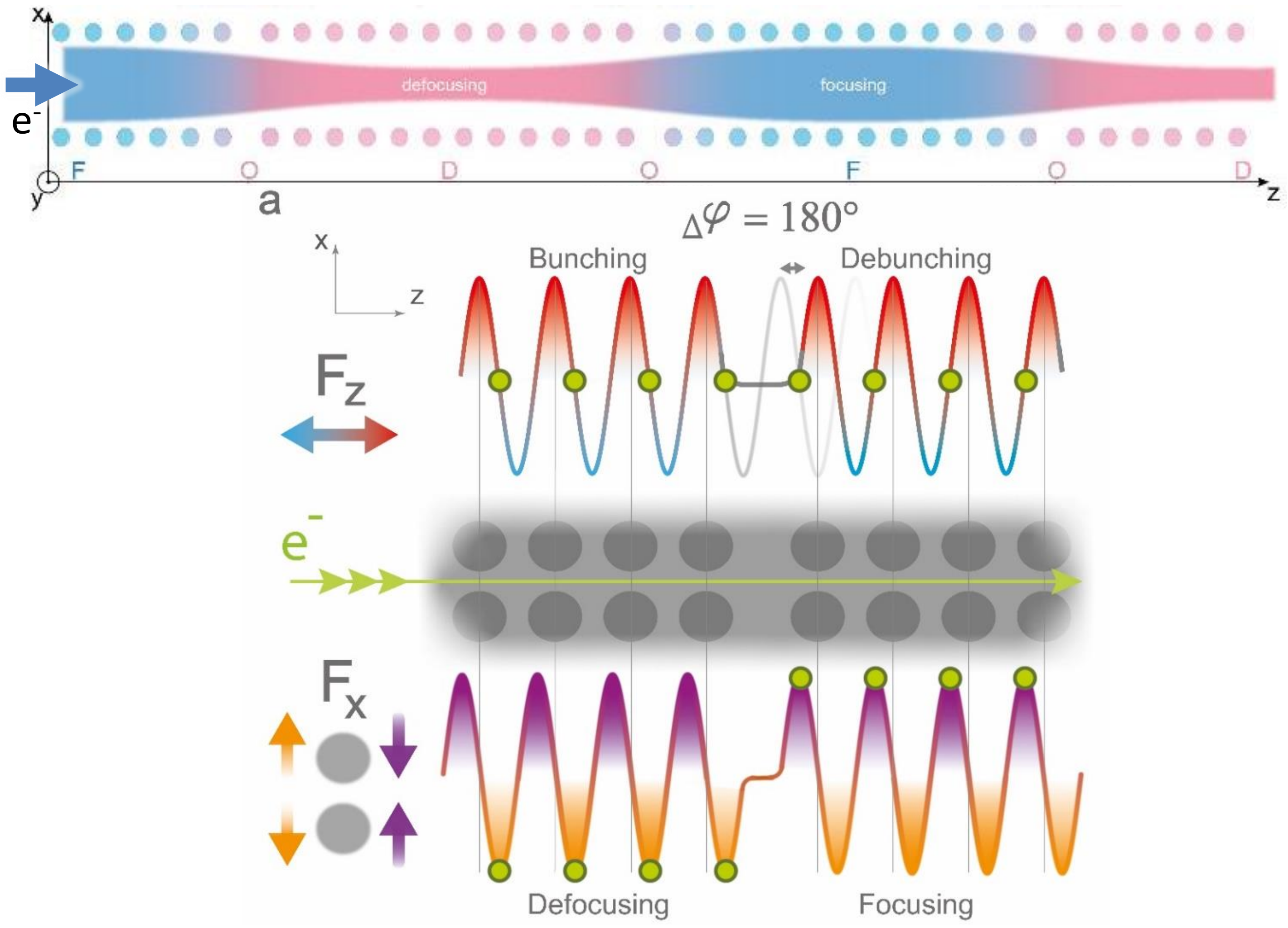
Low (keV) injection energies: strong deflection forces





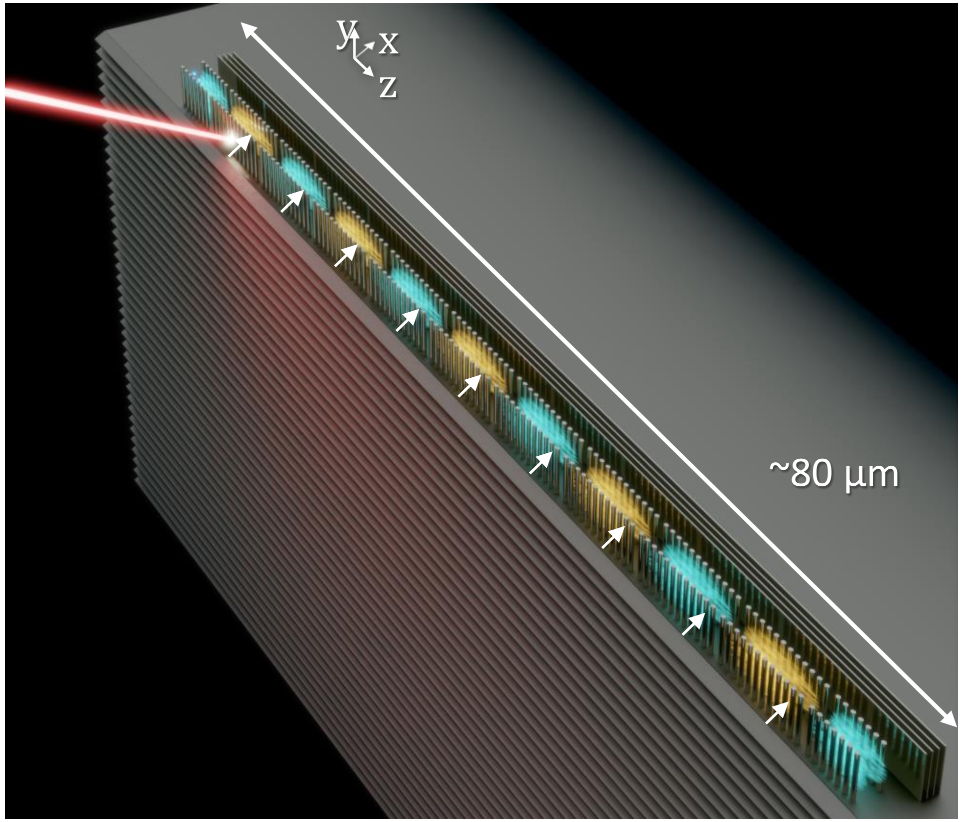
Challenges at keV injection energies

*As presented in EAAC 2021



“Alternating Phase Focusing” (APF)

KEY IDEA: NANOPHOTONIC FODO CELLS

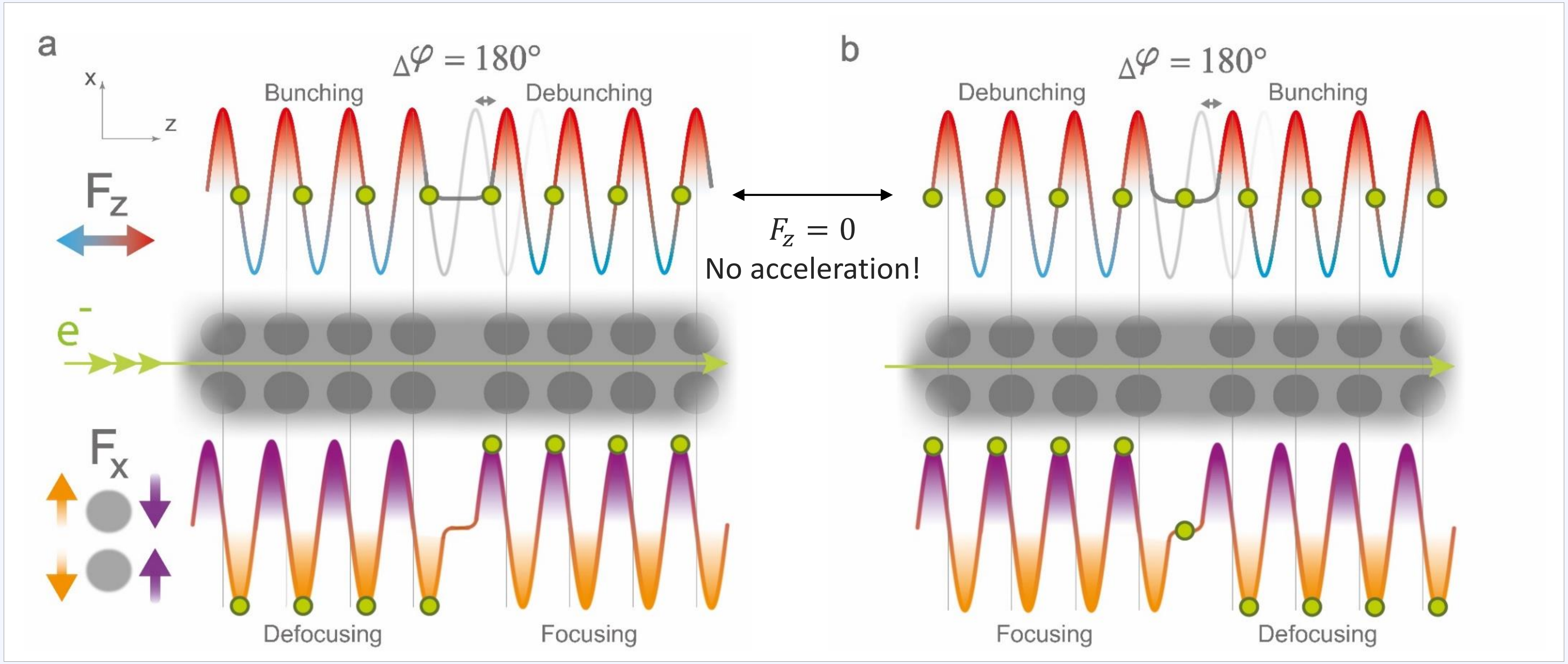


● = Phase matched (velocity to laser field) and synchronized (injected at correct time)

Shiloh*, Illmer*, Chlouba*, et. al., *Nature* **597**, 498-502 (2021)

Niedermayer, Egenolf, Boine-Frankenheim, Hommelhoff, Phys. Rev. Lett. **121**, 214801 (2018)

Beam guiding: Alternating phase focusing



= Phase matched (velocity to laser field) and synchronized (injected at correct time)

Shiloh*, Illmer*, Chlouba*, et. al., *Nature* **597**, 498-502 (2021)
Niedermayer, Egenolf, Boine-Frankenheim, Hommelhoff, Phys. Rev. Lett. **121**, 214801 (2018)

Beam guiding + acceleration

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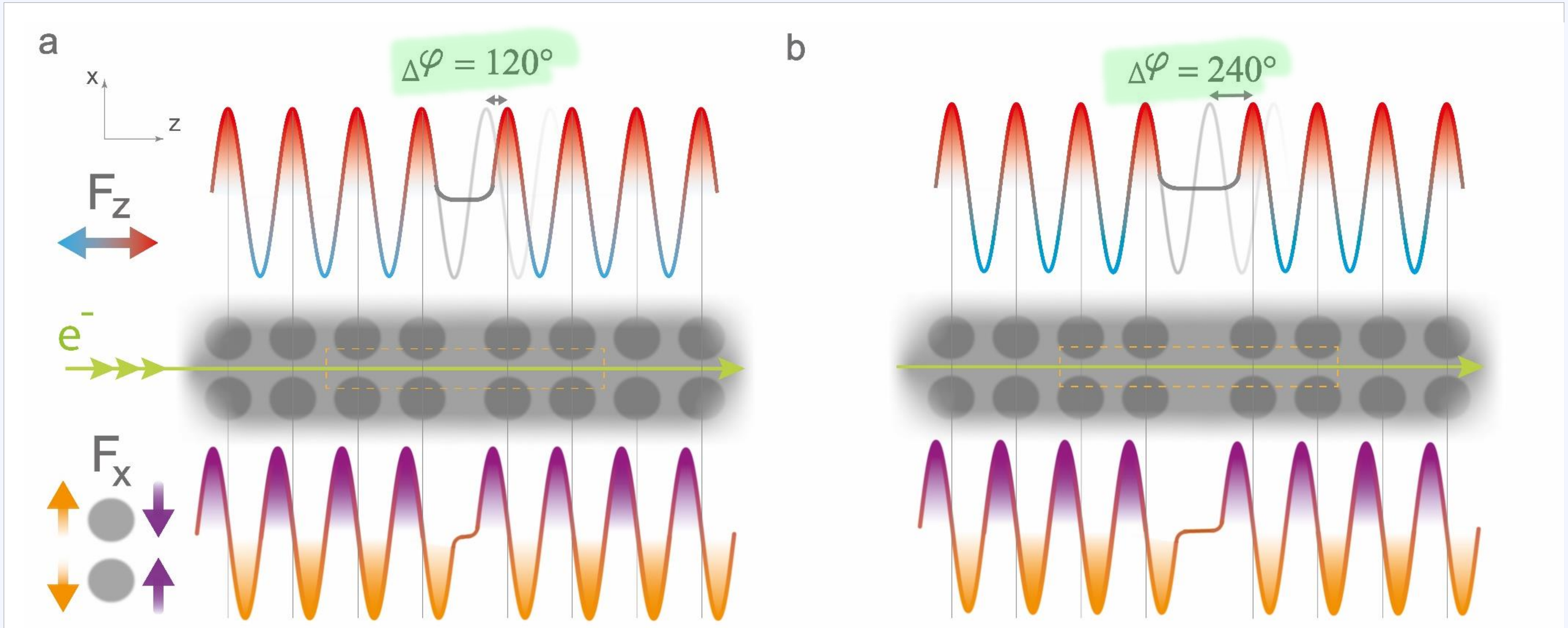

Alternate between phase jumps and **taper** the structure

= Phase matched (velocity to laser field) and synchronized (injected at correct time)

Chlouba, Shiloh, Kraus, Brückner et al., *Nature* **597**, 498-503 (2021)
Shiloh*, Illmer*, Chlouba*, et al., *Nature*, in press (2023)
Niedermayer, Egenolf, Boine-Frankenheim, Hommelhoff, Phys. Rev. Lett. **121**, 214801 (2018)
Niedermayer, Egenolf, Boine-Frankenheim, Hommelhoff, Phys. Rev. Lett. **121**, 214801 (2018)

Beam guiding + acceleration

See talk by Tomáš Chlouba TUE 17:05 WG4

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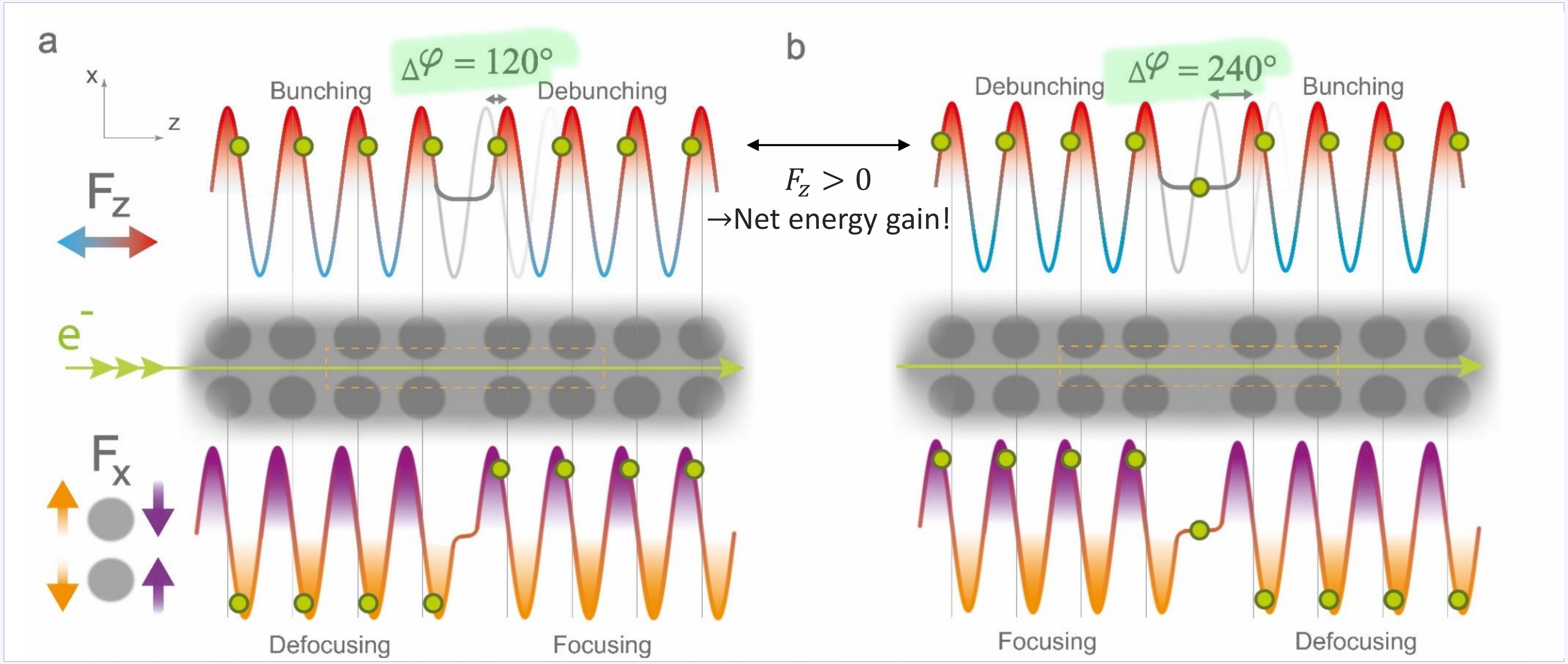

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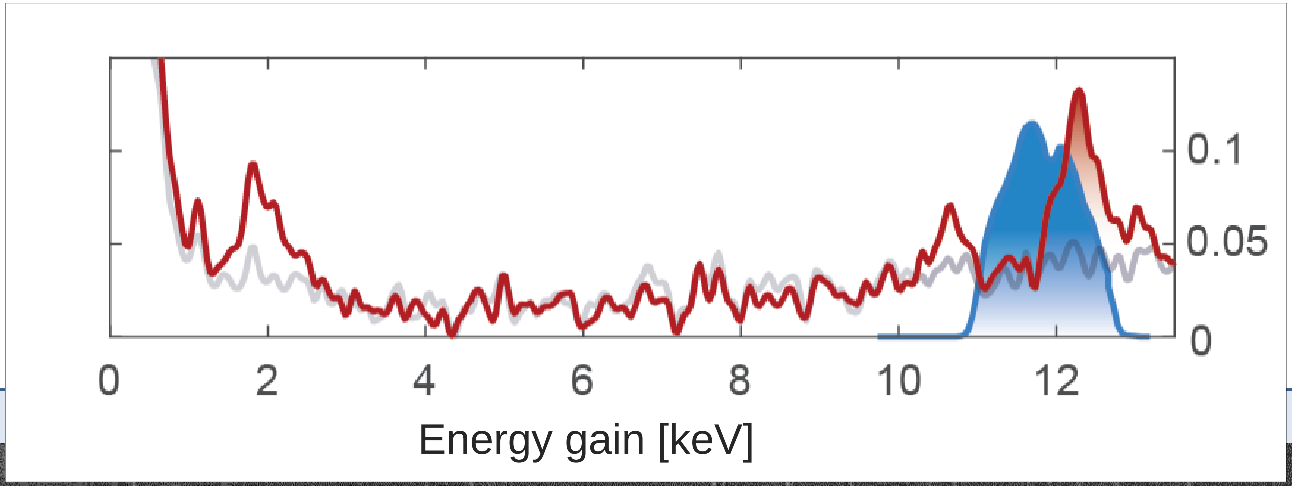
Chlouba*, Shiloh*, Kraus*, Brückner*, et. al., *Nature*, **in press** (2023)
Shiloh*, Illmer*, Chlouba*, et. al., *Nature* **597**, 498-502 (2021)
Niedermayer, Egenolf, Boine-Frankenheim, Hommelhoff, Phys. Rev. Lett. **121**, 214801 (2018)

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM
roy.shiloh@mail.huji.ac.il

Scalable accelerator: *proof of concept* measurement

<u>Structure properties</u>

500 µm long, made of 733 pillar pairs
Tapered periodicity: from 619 nm to 717 nm
Tapered macro-cells: from 5 µm to 22.5 µm (total of 26 segments)
Average design gradient: 22.7 MeV/m



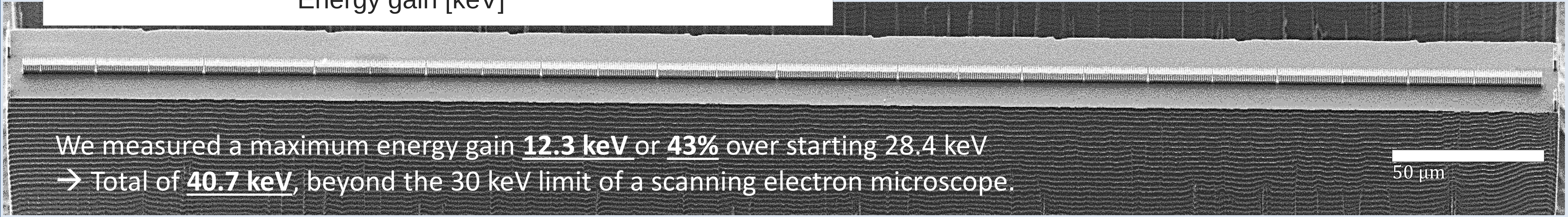
<u>Electron beam properties</u>

Injection electron energy:	**28.4 keV +/- 0.0007 keV**
Normalized emittance:	**100 pm-rad**
Electron pulses:	400-600 fs (FWHM)
Repetition rate:	SAME AS LASER

<u>Laser properties</u>

Wavelength:	1.93 µm
Laser pulse:	250 fs
Repetition rate:	167 kHz

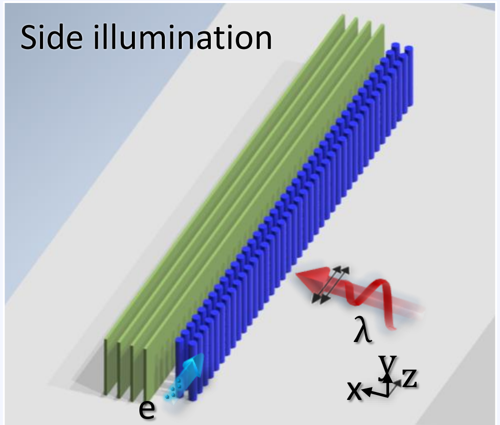
Peak electric optical field: 600 MV/m (2.2 µJ pulse energy and 360 mW average, **8.8 MW peak power**)

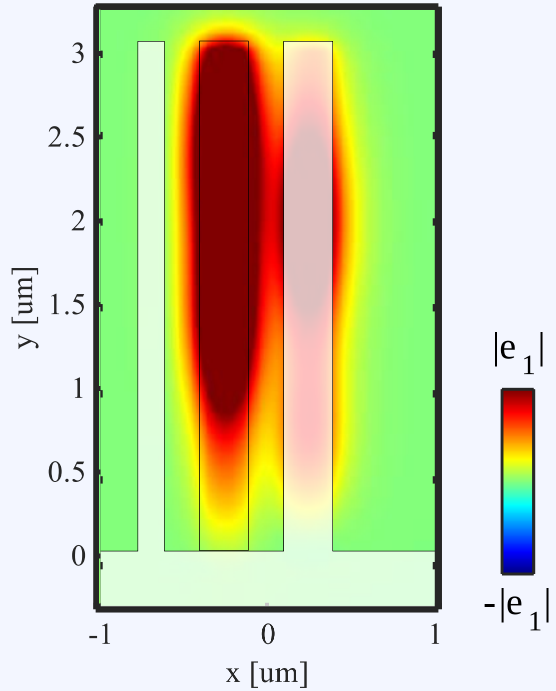


We measured a maximum energy gain <u>12.3 keV</u> or <u>43%</u> over starting 28.4 keV
→ Total of <u>40.7 keV</u>, beyond the 30 keV limit of a scanning electron microscope.

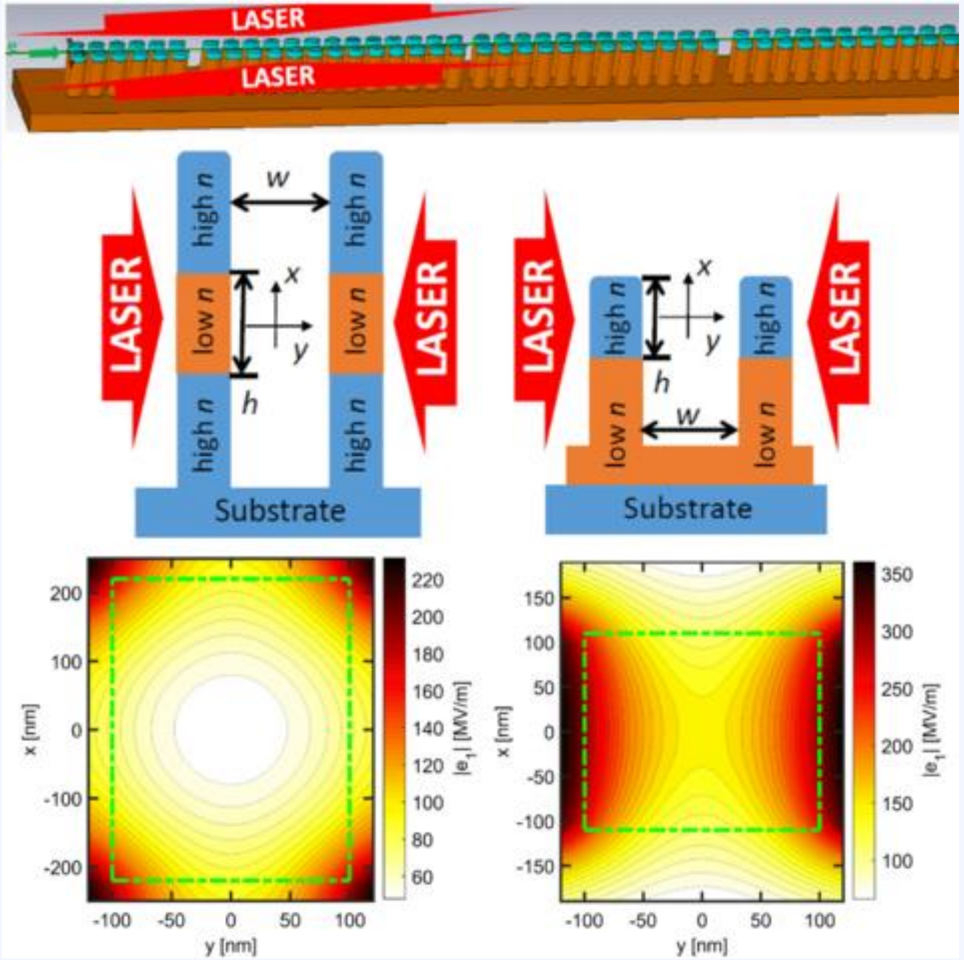
Chlouba*, Shiloh*, Kraus*, Brückner*, Litzel, Hommelhoff, *Nature*, **in press** (2023)

Next challenge (sub-relativistic) DLA: net 3D confinement

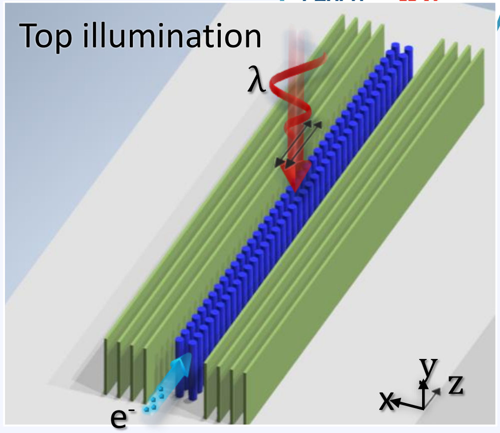


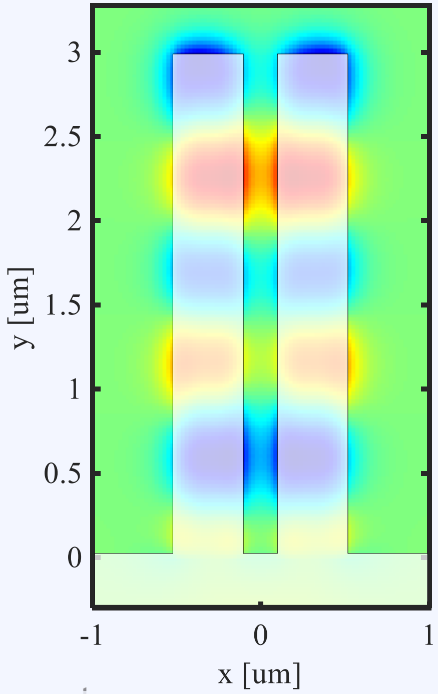


Extended lengths: the vertical transverse direction



Niedermayer, Egenolf, Boine-Frankenheim
Phys. Rev. Lett. **125**, 164801 (2020)





Shiloh, Chlouba, Yousefi, Hommelhoff
Opt. Exp. **29**, 14403 (2021)

Conclusion: Dielectric Laser Accelerators

LASER PHYSICS FAU

Recent results

- First experimental results from the ARES beamline (DESY) (100-150 MeV)
- Preliminary results from the Pegasus facility (UCLA) (6 MeV)
- First scalable, acceleration results in the sub-relativistic regime from Erlangen and Stanford (30-100 keV)

Applications (Sub-relativistic electrons)

- Single-electron wavepackets = fundamental quantum light-matter physics
- Compact high-energy (100's of keV) ultrafast electron microscopes
- Attosecond-Angstrom ultrafast electron microscopy

REVIEW PAPERS:

Shiloh et al., Adv. Opt. Photon. **14**, 862-932 (2022)

Wootton, McNeur, Leedle, Rev. of Accel. Sci. and Tech. **9**, 105-126 (2016)

England et al., Rev. Mod. Phys. **86**, 1337 (2014)

ACHIP Accelerator on a Chip International Program

FAU Friedrich-Alexander-Universität Naturwissenschaftliche Fakultät

DFG bmb+f

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