Silicon nano-structures for dielectric laser accelerators: fabrication, simulation and testing

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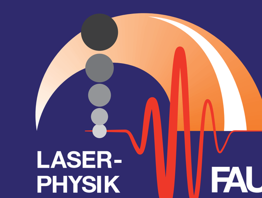
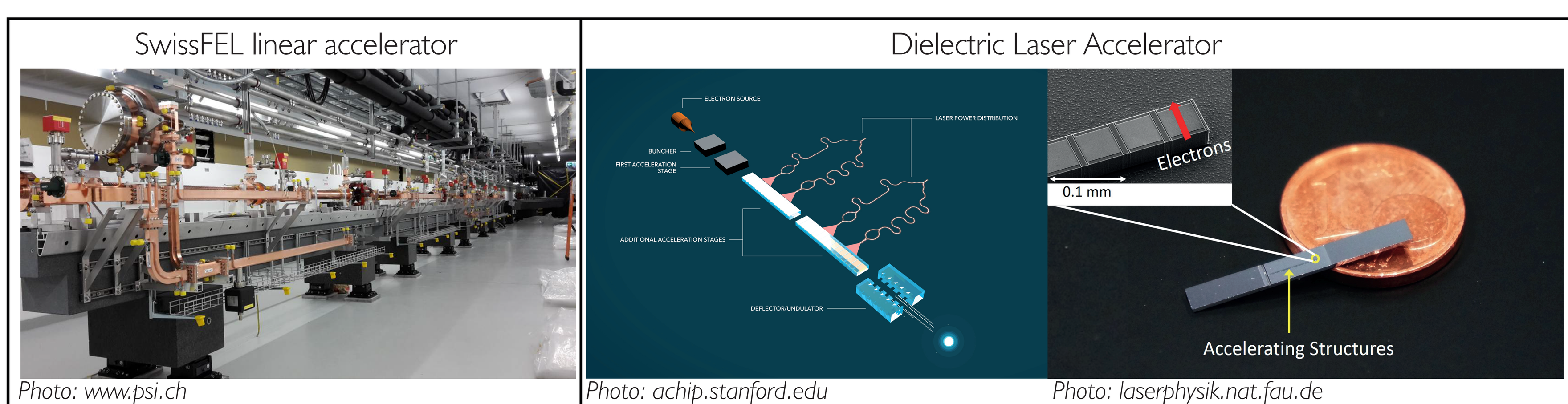


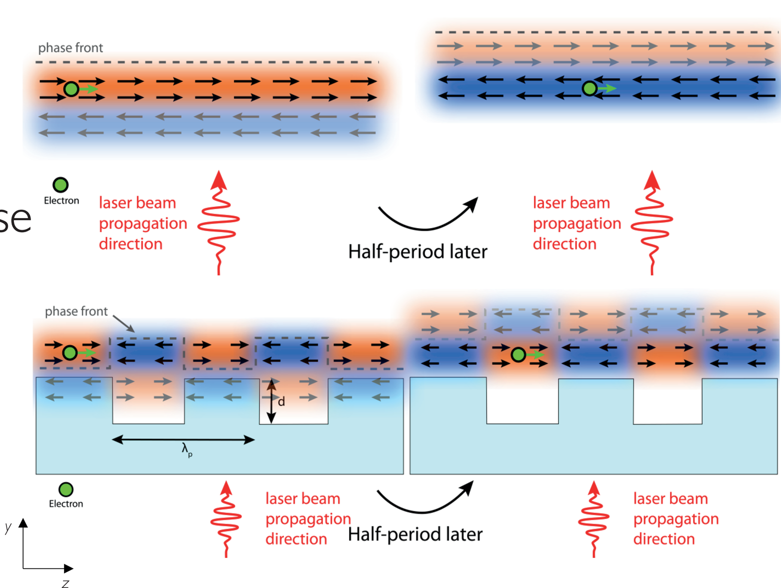
Motivation

- Miniaturizing the current RF particle accelerators: > cm feature size to <µm feature size.
- Higher acceleration gradients due to higher damage threshold of dielectrics compared to metal cavities.
- Cost reduction for many scientific applications such as table top free electron lasers for real time molecular imaging and also for medical applications such as cancer therapy [1].



Concept

- Excitation of near-field modes at a photonic structure by short pulse lasers.
- Synchronicity condition:
  Electron velocity should be matched with the phase velocity in order to accelerate.
  $\lambda_p = m\beta\lambda$ (m=1,2,3,...)
  (m: # of laser cycles per electron passing one period.
  $\beta = v/c$, v: electron velocity, λ: laser wavelength)

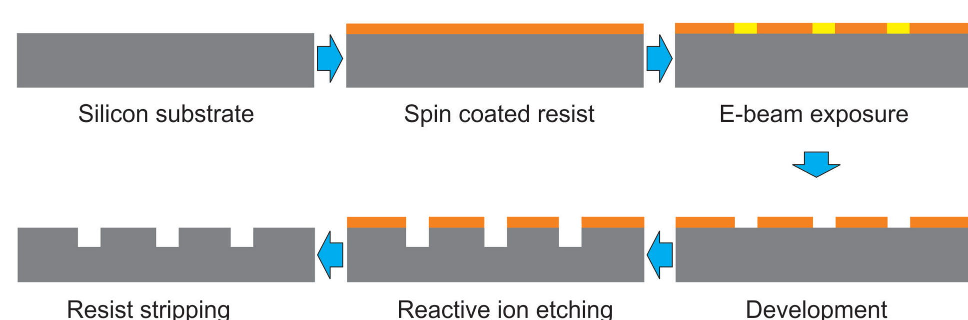


- Strong electric field in excess of 10^9 V/m can be applied due to high damage threshold of dielectrics.
- Acceleration gradient as high as 10 GeV/m is achievable [2,3].
- Damage threshold: Dielectrics with higher laser damage thresholds are neccesary for higher acceleration factors (G_{acc}/eE_{inc}); G_{acc}=Acceleration gradient, E_{inc}=Incident electric field
- Double sided structures: More spatially uniform fields in the *y*-direction.

Fabrication Process for DLA Structures

- Electron beam lithography

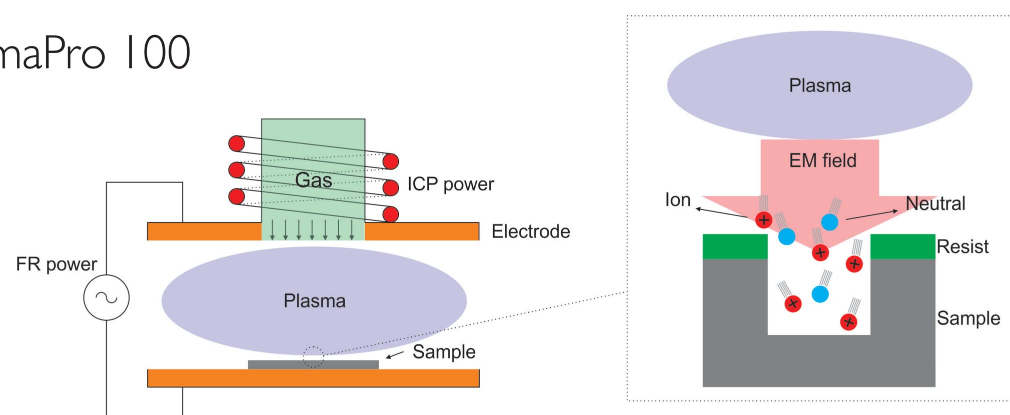
E-beam resist: ma_N2405
E-beam system: Raith (30 kV)



- Reactive ion etching

Highly anisotropic etching technique for high aspect ratio geometries.
Inductive coupled plasma (ICP) for high density plasma delivery [4].

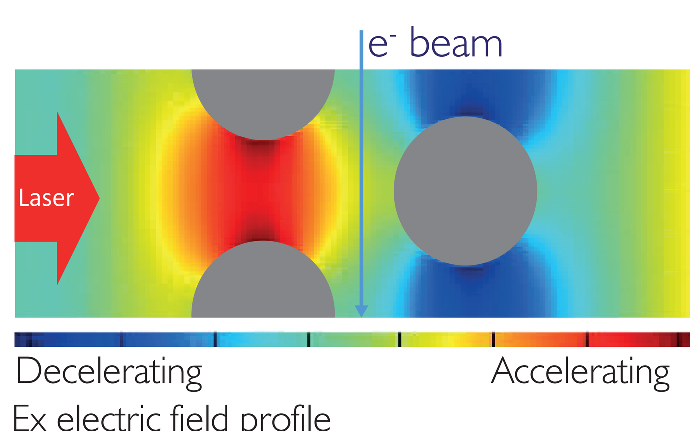
RIE system: Oxford Instruments-PlasmaPro 100
- Etching gases for silicon: SF6/O2
- Cryogenic conditions at -120°C
- Etch rate: 31 nm/s



Simulations

Dual pillars structure

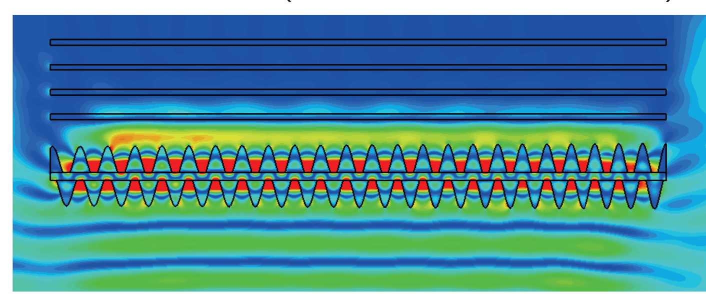
- Symetric field confinment between pillars
- Higher acceleration factor.



Ex electric field profile

Sinusoidal structure

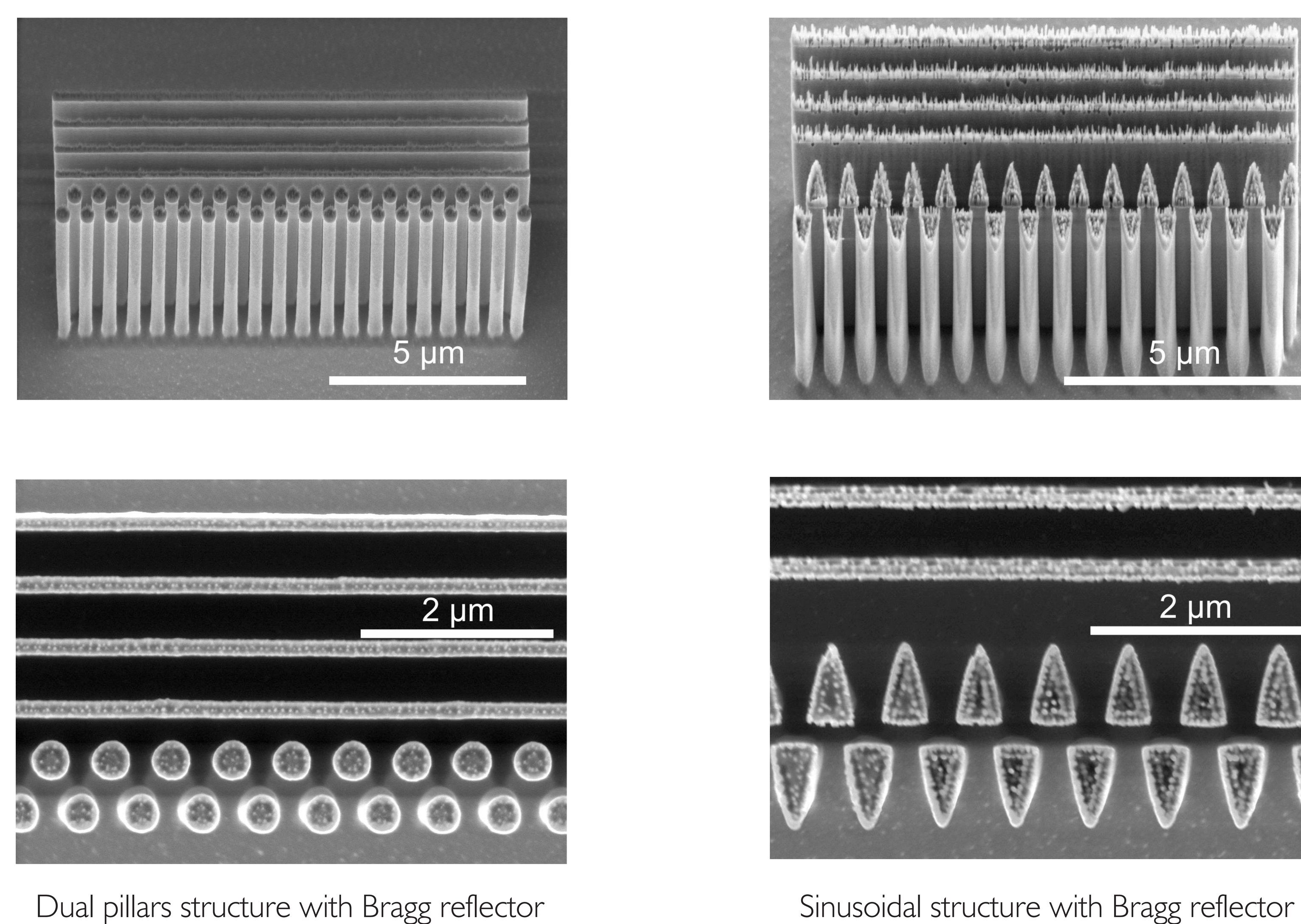
- Acceleration factor > 70%
- This would enable gradients of >1 GeV/m (for 30 keV electrons)



Simulation performed by Uwe Niedermayer from TU Darmstadt

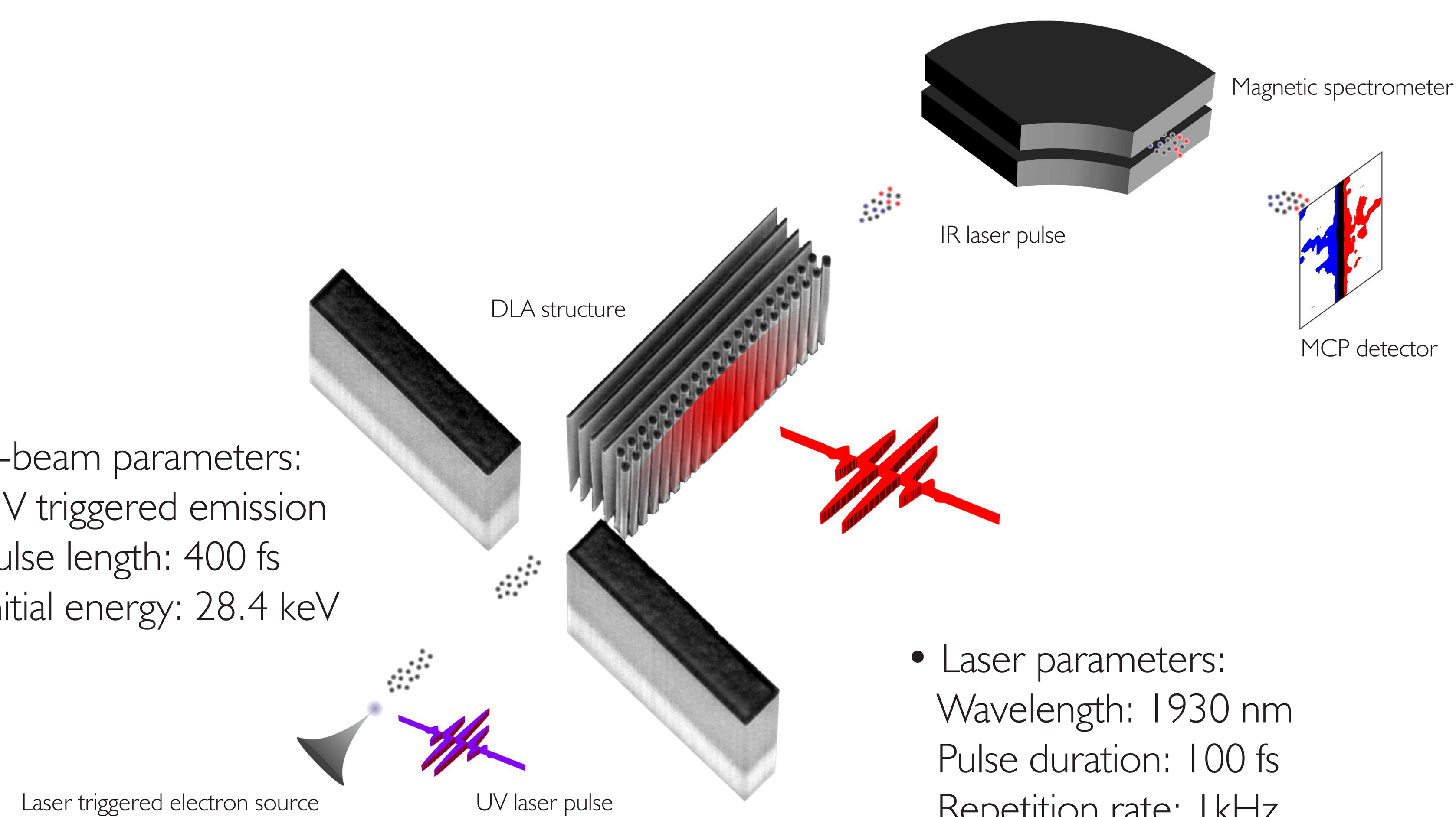
DLA Structures

- Two different geometries have been fabricated out of silicon using E-beam lithography and reactive ion etching techniques. They have been etched to 3 micron depth.



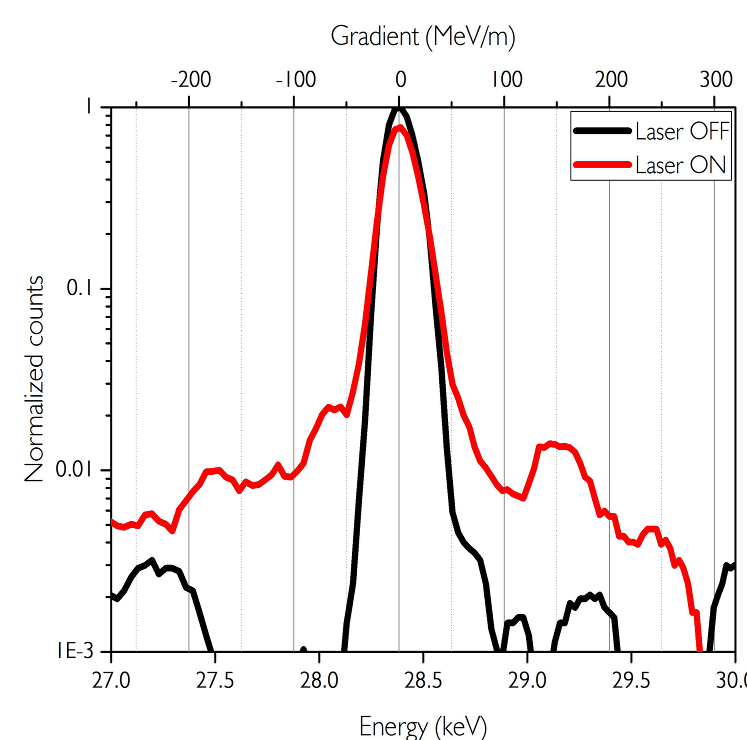
Dual pillars structure with Bragg reflector — Sinusoidal structure with Bragg reflector

Experimental Setup and Results

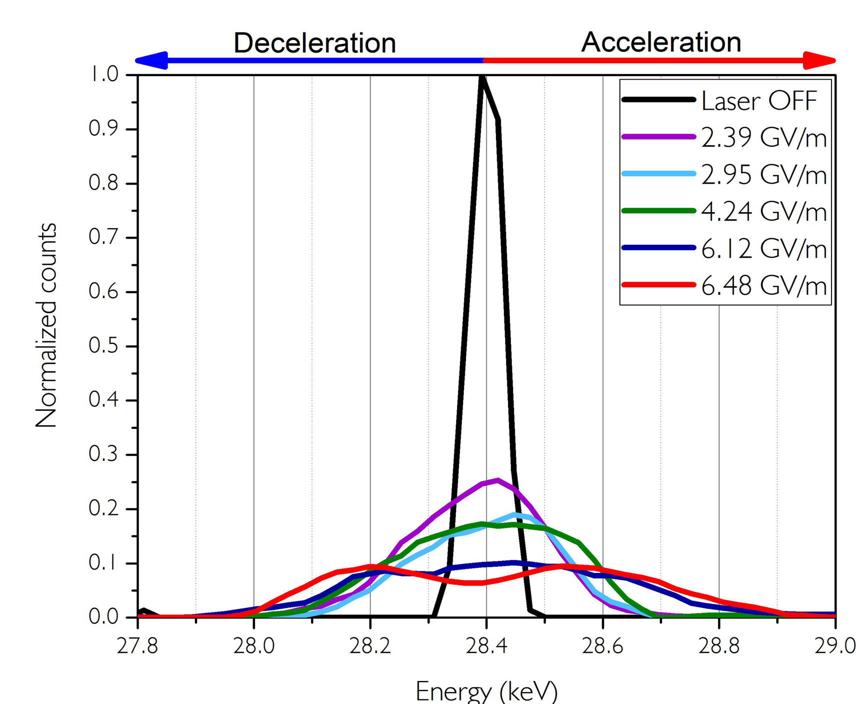


- E-beam parameters:
  UV triggered emission
  Pulse length: 400 fs
  Initial energy: 28.4 keV

- Laser parameters:
  Wavelength: 1930 nm
  Pulse duration: 100 fs
  Repetition rate: 1kHz



- Maximum gradient of 150 MeV/m is achieved by 100 fs laser pulses with a peak electric field of 5.5 GV/m.



- 640 fs laser pulses generated by passing 100 fs pulse through narrow bandwidth filter at 1930 nm. This makes almost all the electrons intract with the incident laser pulse, however reduces the maximum acceleration gradient at the same time.

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References: [1] J. England, et al., Reviews of Modern Physics. 86, 1337-1389 (2014).
[2] J. Breuer, P. Hommelhoff, PRL 111, 134803 (2013).
[3] E. Peralta, et al., Nature 503, 91-94 (2013).
[4] M. Sugawara, Plasma Etching, Oxford University Press Inc., (1998).