LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Technische Universität München

Center for Advanced Laser Applications

CALA

Injection and beamloading of high-charge electron bunches

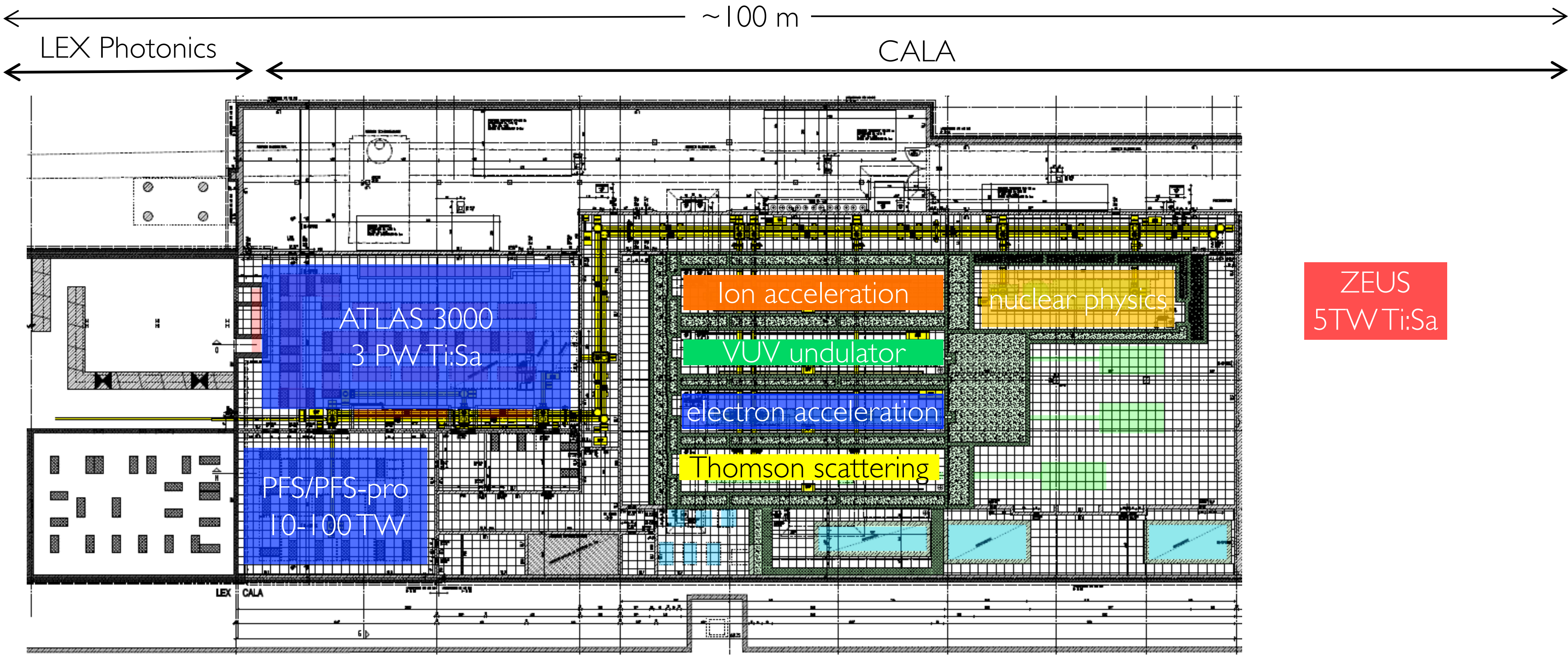
Stefan Karsch

Ludwig-Maximilians-Universität München/

MPI für Quantenoptik

Garching, Germany

CALA - Building layout

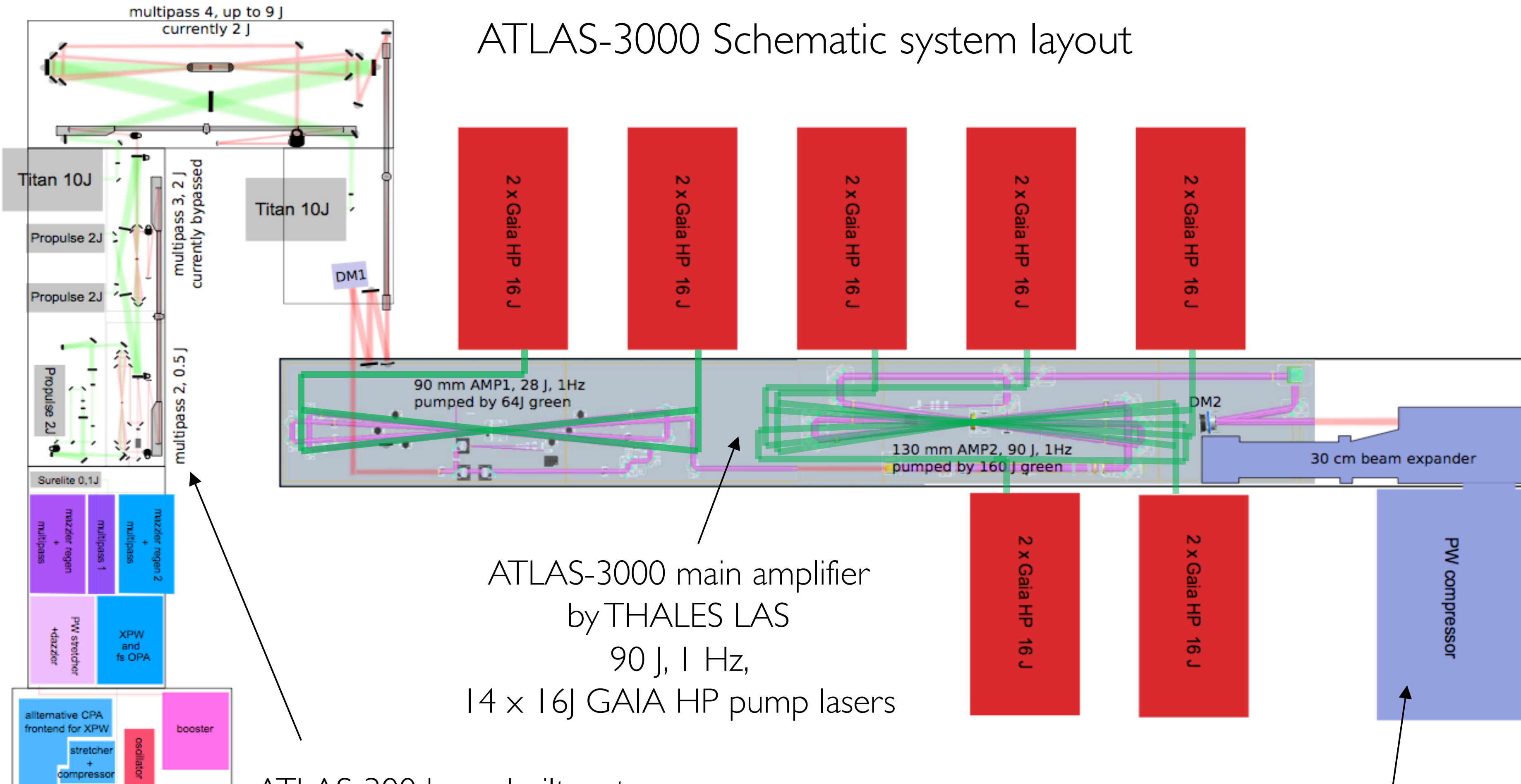


- 75 M€ infrastructure to explore laser applications for medical research:
- 2 pillars:
  - molecular fingerprinting by infrared ringdown spectroscopy for cancer detection (F. Krausz)
  - Laser-driven X-rays for tumour localization and ion beams for radiation oncology (J.Schreiber, S. Karsch)

A. Döpp, L. Doyle, M. Förster, K. v. Grafenstein, F. Haberstroh, J. Hartmann, C. Lin, T. Rösch, G. Schilling, E. Travac:

ATLAS-3000

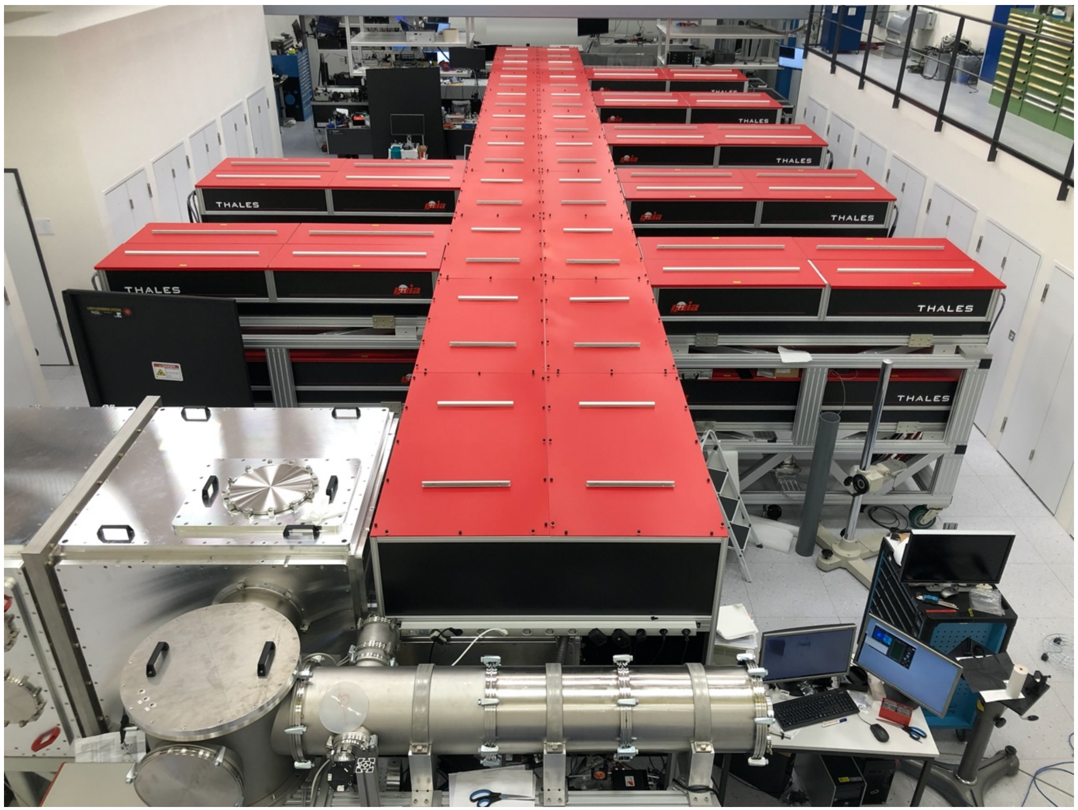
ATLAS-3000 Schematic system layout



ATLAS-3000 main amplifier
by THALES LAS
90 J, 1 Hz,
14 x 16J GAIA HP pump lasers

ATLAS-300 homebuilt system:
up to 300 TW, 25 fs, 5 Hz Ti:Sa laser
2 frontends:
- ps booster, sat. absorber + Amplitude stretcher & regen
- double CPA, XPW + fs-OPA + Amplitude stretcher & regen

Homebuilt beam
expander & compres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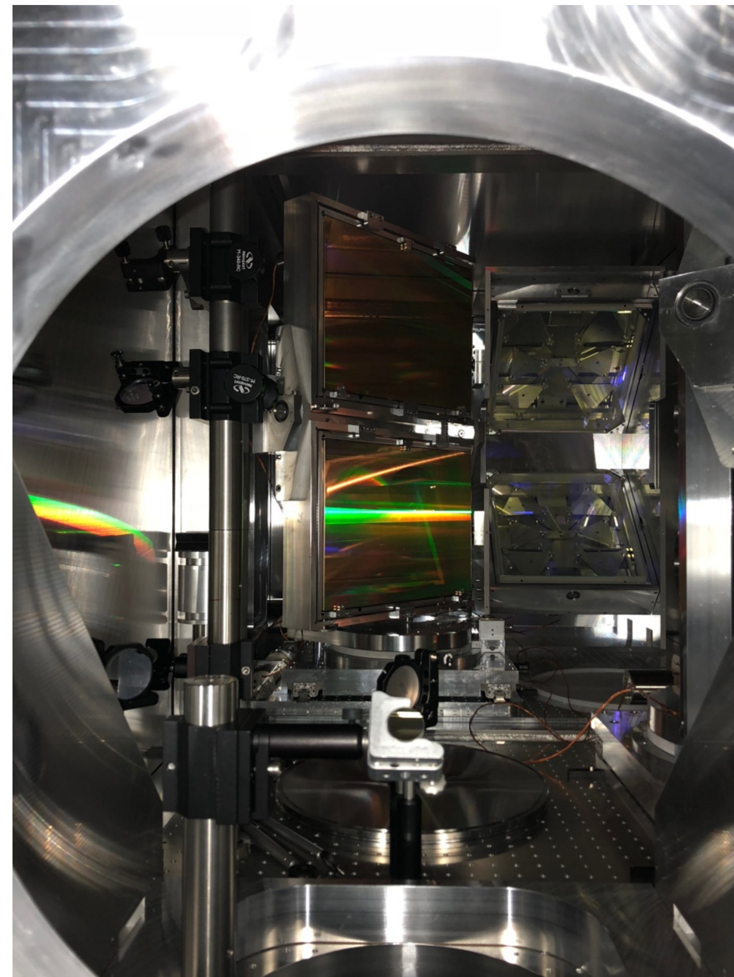
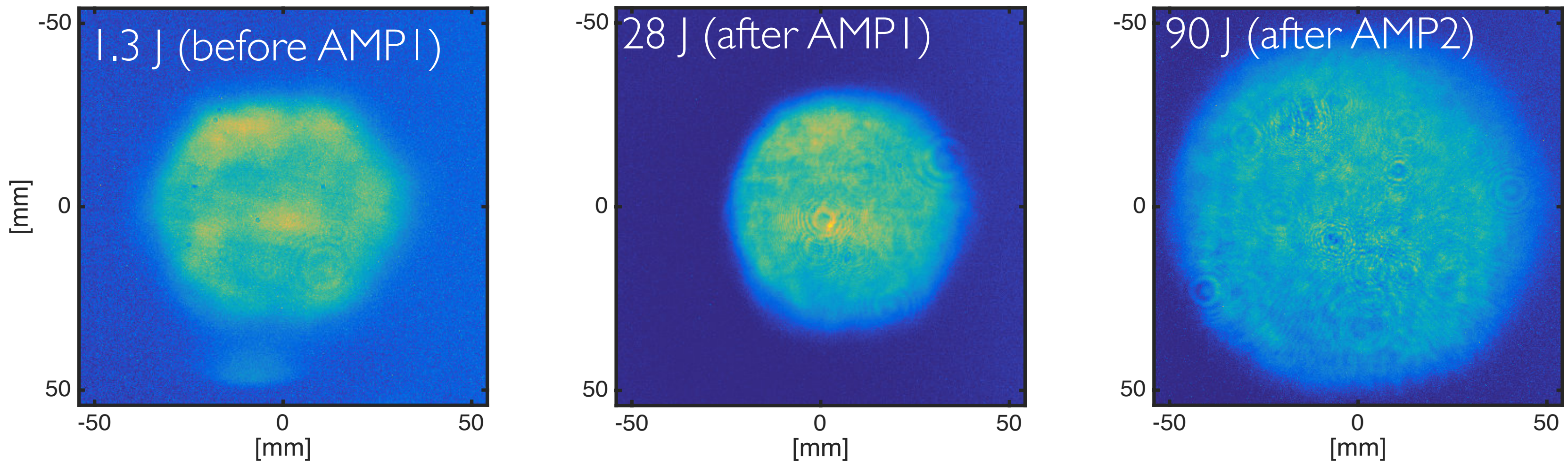


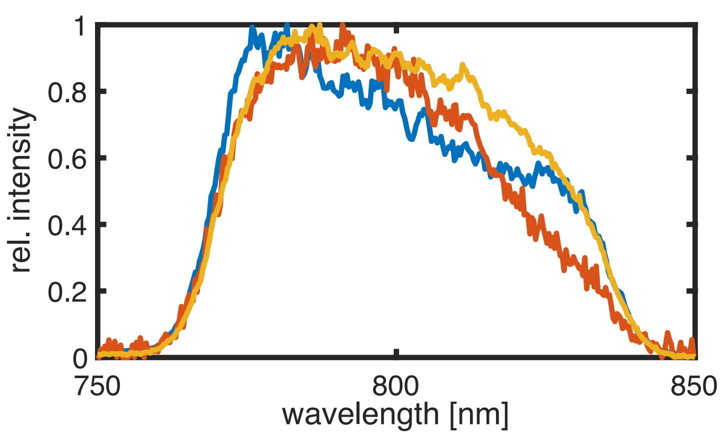
ATLAS-3000 amplifier performance

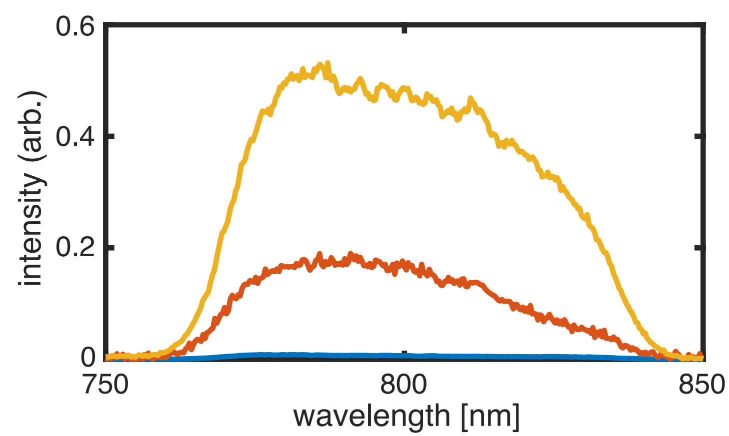


before AMP1
1.3 J

after AMP1
28 J

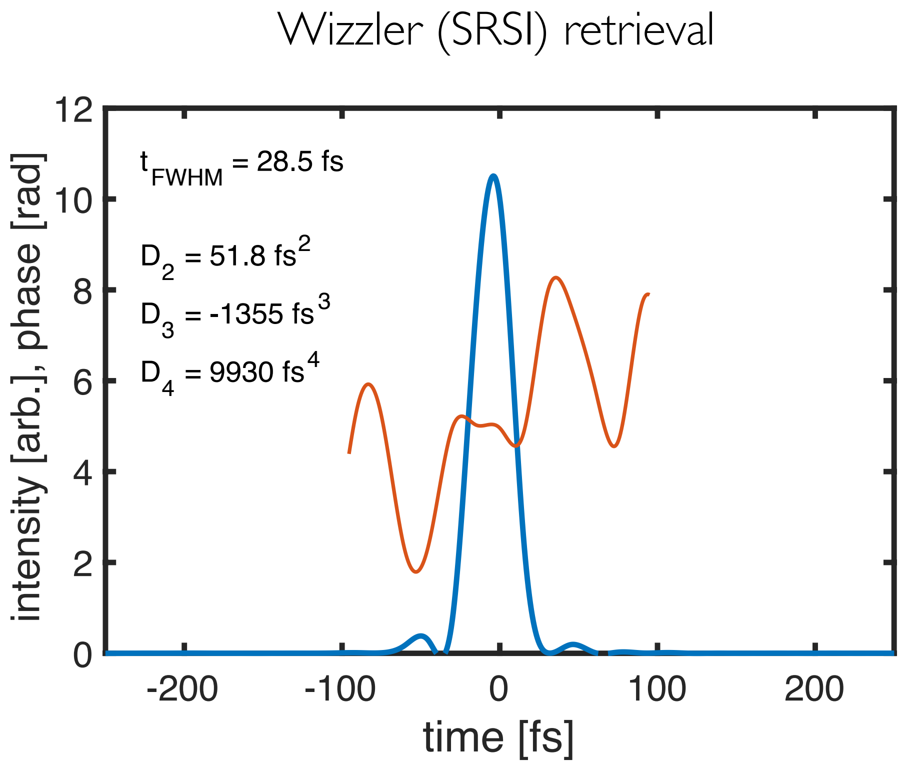
after AMP2
90J

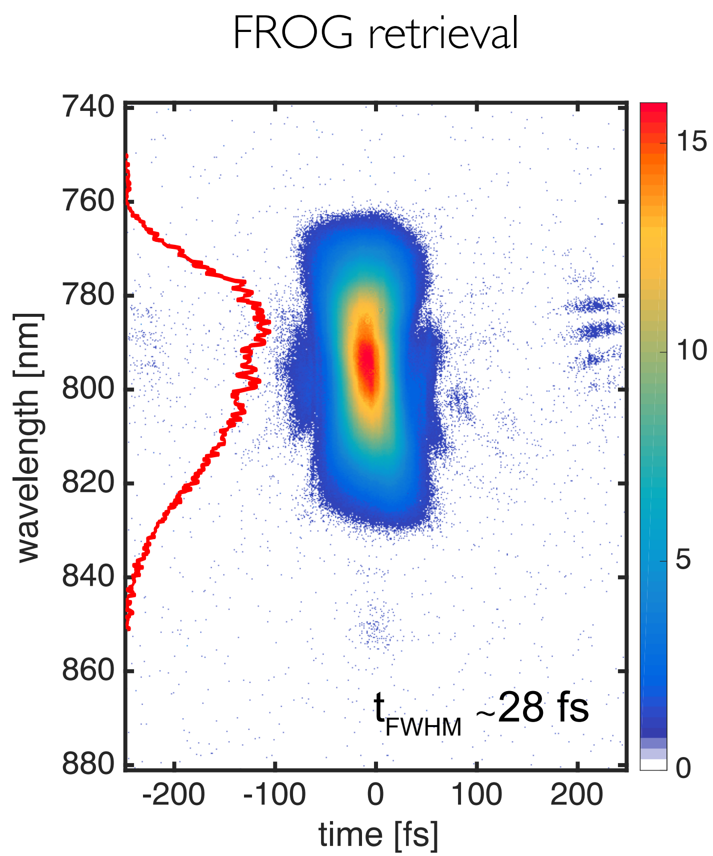




Even at 90J, the gain narrowing/redshift is well under control!

Compression (9 J, full-size 30 cm diameter beam)



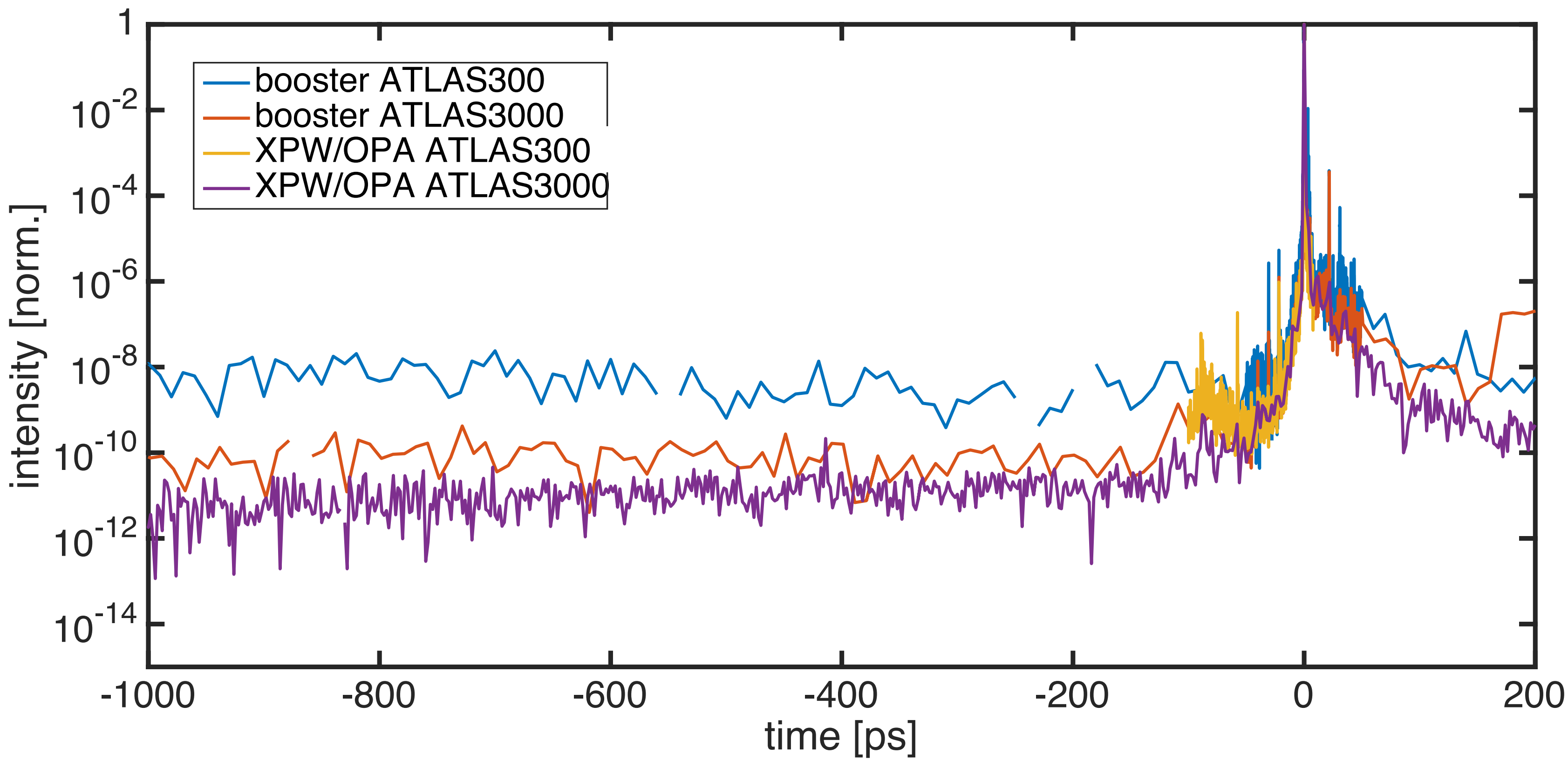


Current energy level : 3 Gaias out of 14: 18 J after Amp 1

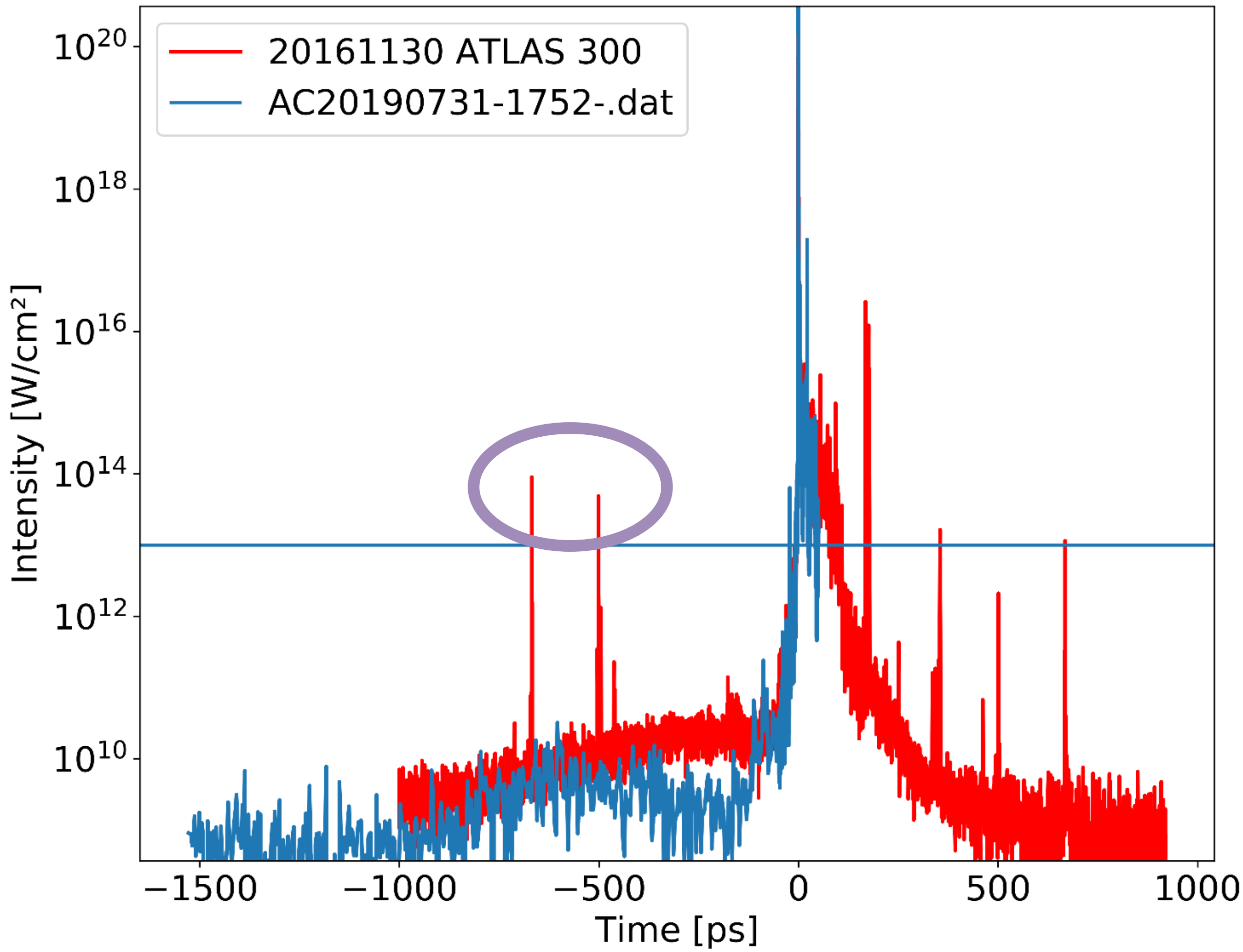
Passive Amp2 + Compressor + beamline throughput ~ 50 – 55 %

Energy on target: 9-10 J (estimate), 280 – 330 TW

Contrast


booster ATLAS300
booster ATLAS3000
XPW/OPA ATLAS300
XPW/OPA ATLAS3000
intensity [norm.]
1
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
-1000
-800
-600
-400
-200
0
200
time [ps]

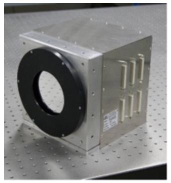
Laser pulse temporal contrast – comparison with old ATLAS

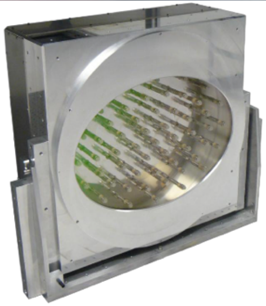


-> got rid of the pre-pulses, contrast is quite good

-> try to start laser-driven ion acceleration

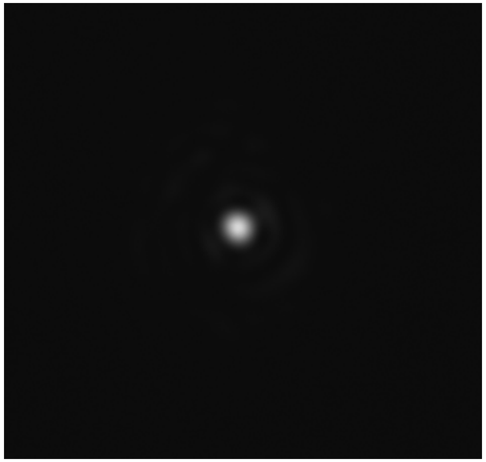
Focal spot quality on target: 3 deformable mirrors





Mirror 1: flat wavefront at frontend output for good near field propagation in main amp.
Mirror 2: flat wavefront before compression
Mirror 3: corrects aberrations in compressor and beamline, wavefront sensor at target position

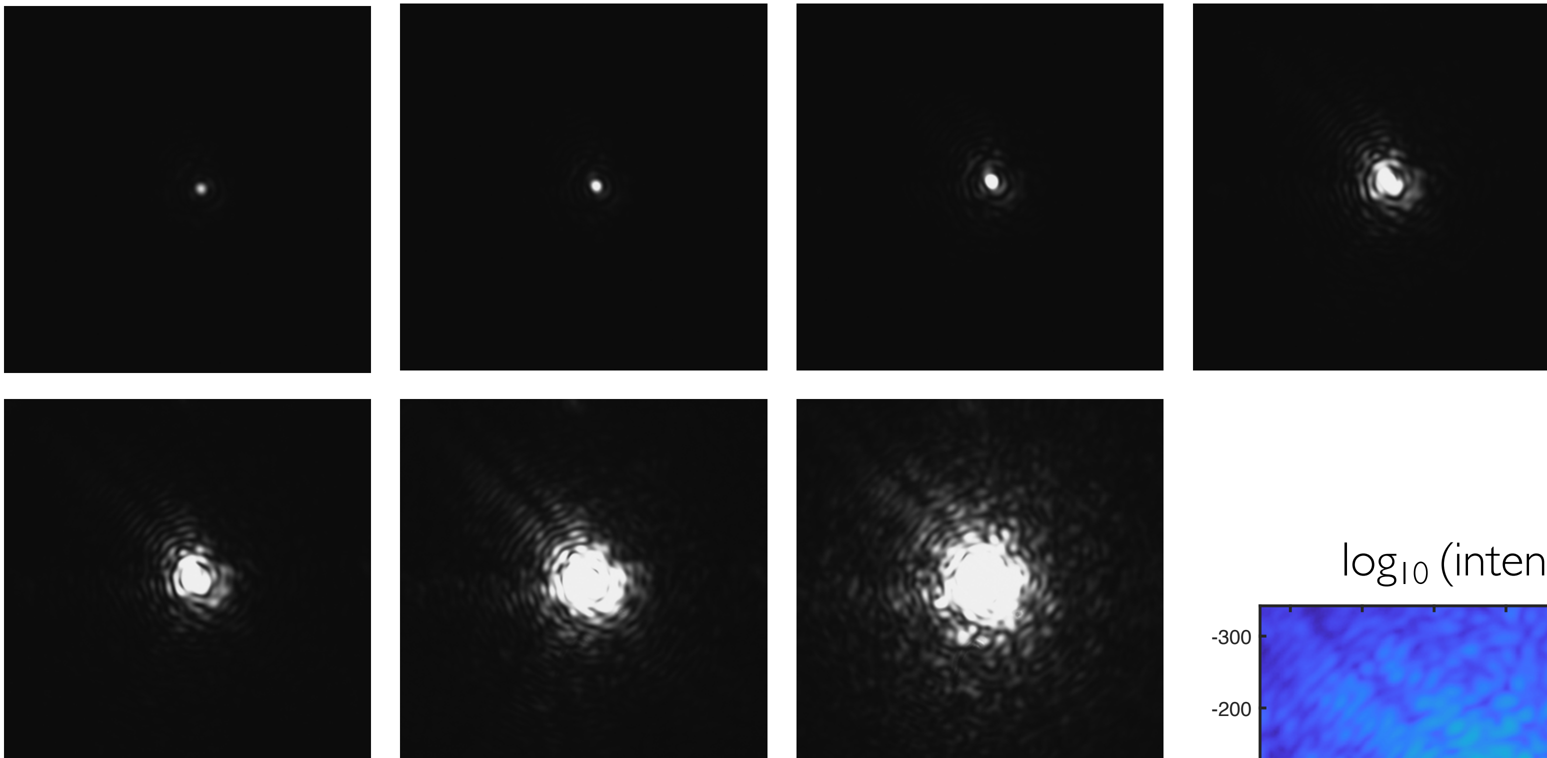
Nice focus, isn‘t it?

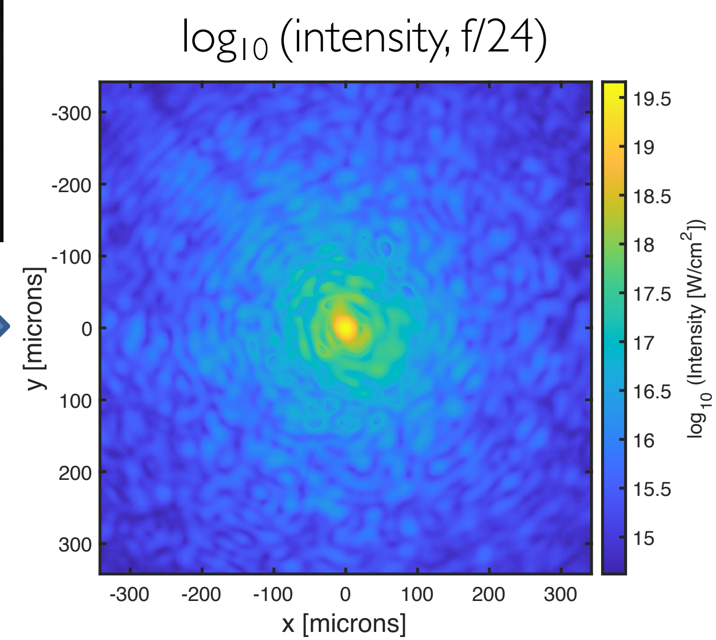


Jumps around, so we have to average…

Remaining issues: Pointing and focus “breathing“ due to air turbulence.

After registration and averaging over 10 shots: foci with seven different filter settings:

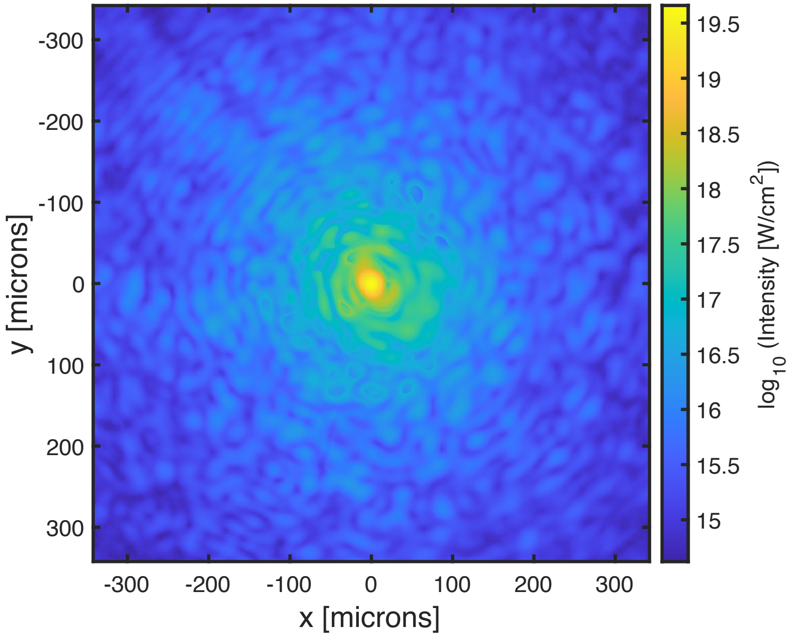




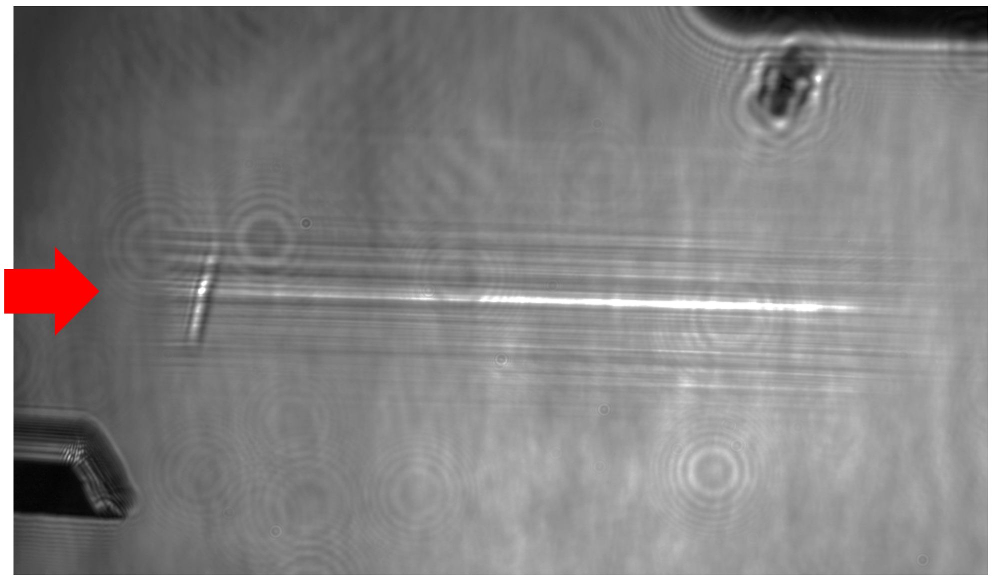
Scattering in optics leads to pedestal of high frequency noise, containing a significant amount of energy

Scattering in optics leads to pedestal of high frequency noise, containing a significant amount of energy

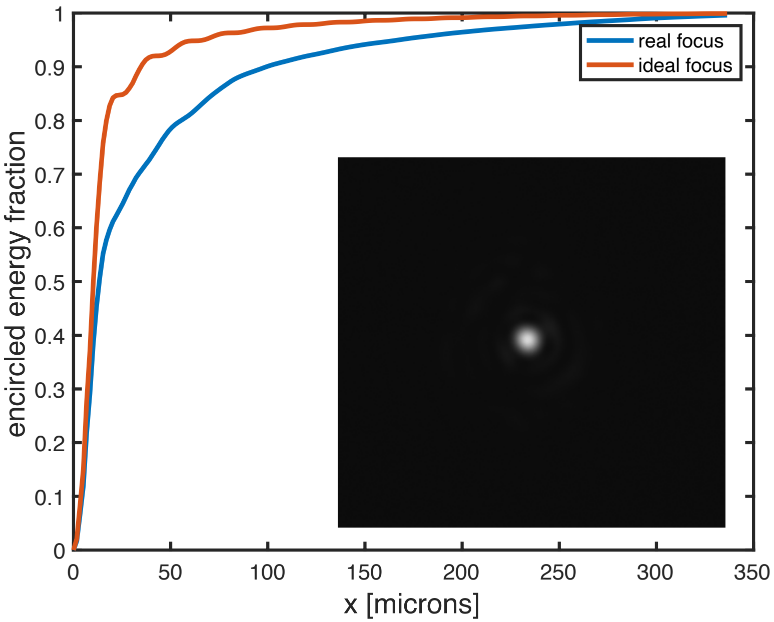
Speckles outside focus…



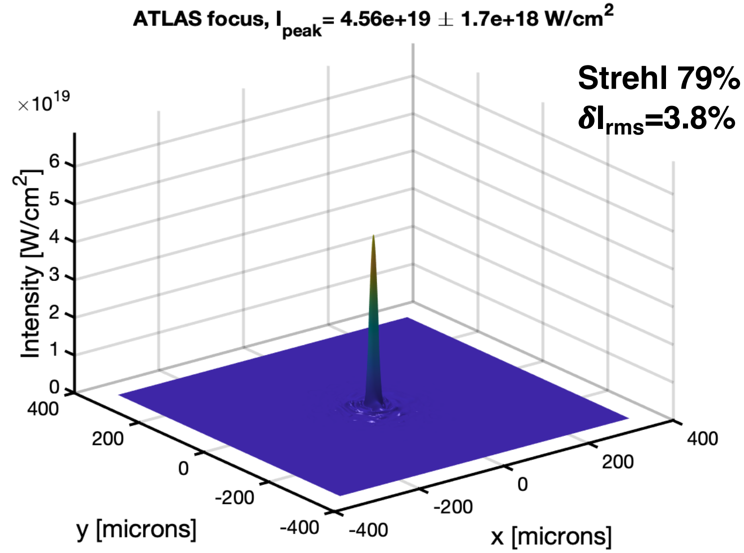
… lead to striations in probe image (non-uniform plasma density)



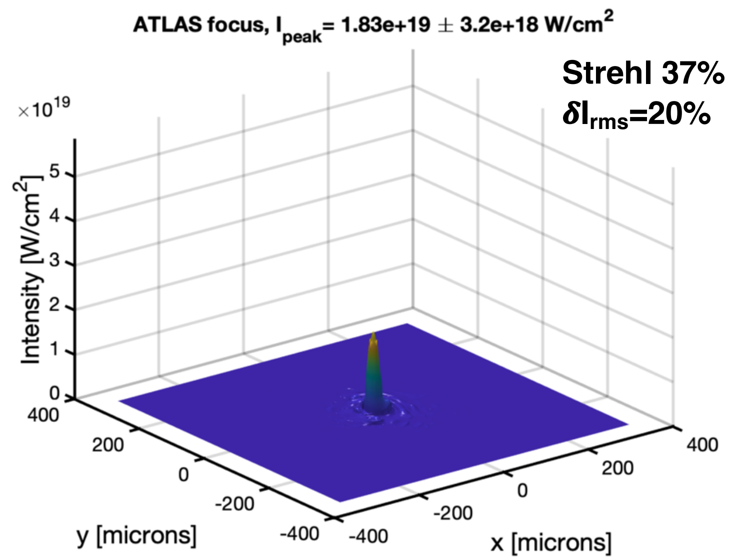
Encircled energy fraction (fractional energy within radius x) reveals real Strehl ratio



In focus, good WF correction



Slightly out of focus, ok WF correction



Slightly out-of-focus, the intensity fluctuations increase drastically! Stable laser-plasma interaction requires a high degree of focus correction and a Rayleigh length exceeding the plasma gradient.

New approach: Measure wavelength-dependent focus or wavelength dependent spatial phase to reveal full field distribution (Andreas Döpp & Univ. Oxford)

Focusability: Key quantity for good experiment performance

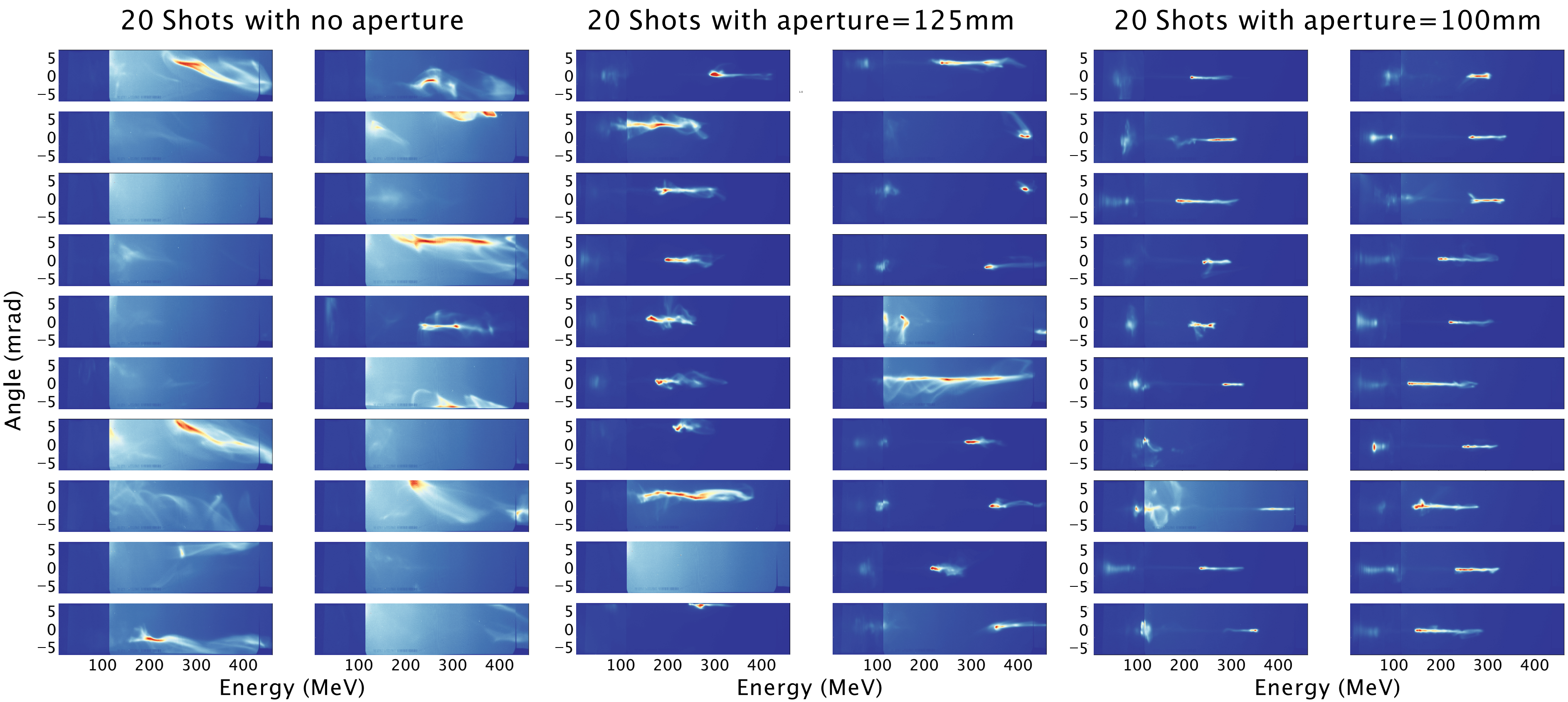
- Focusability determines intensity
- Under random phase fluctuations (air turbulence) the intensity stability is better in focus than close to it.
- Outside of focus, near-field intensity variations cause random self-focusing and pointing fluctuations: Rayleigh length should be longer than plasma density gradient.

Maier et al., PRX 10, 031039 (2020) identifies the influence of laser energy, focus position and laser direction on electron peak energy.

We investigate the influence of one parameter (focus quality at shock position) on stability (energy, pointing jitter, monochromaticity)

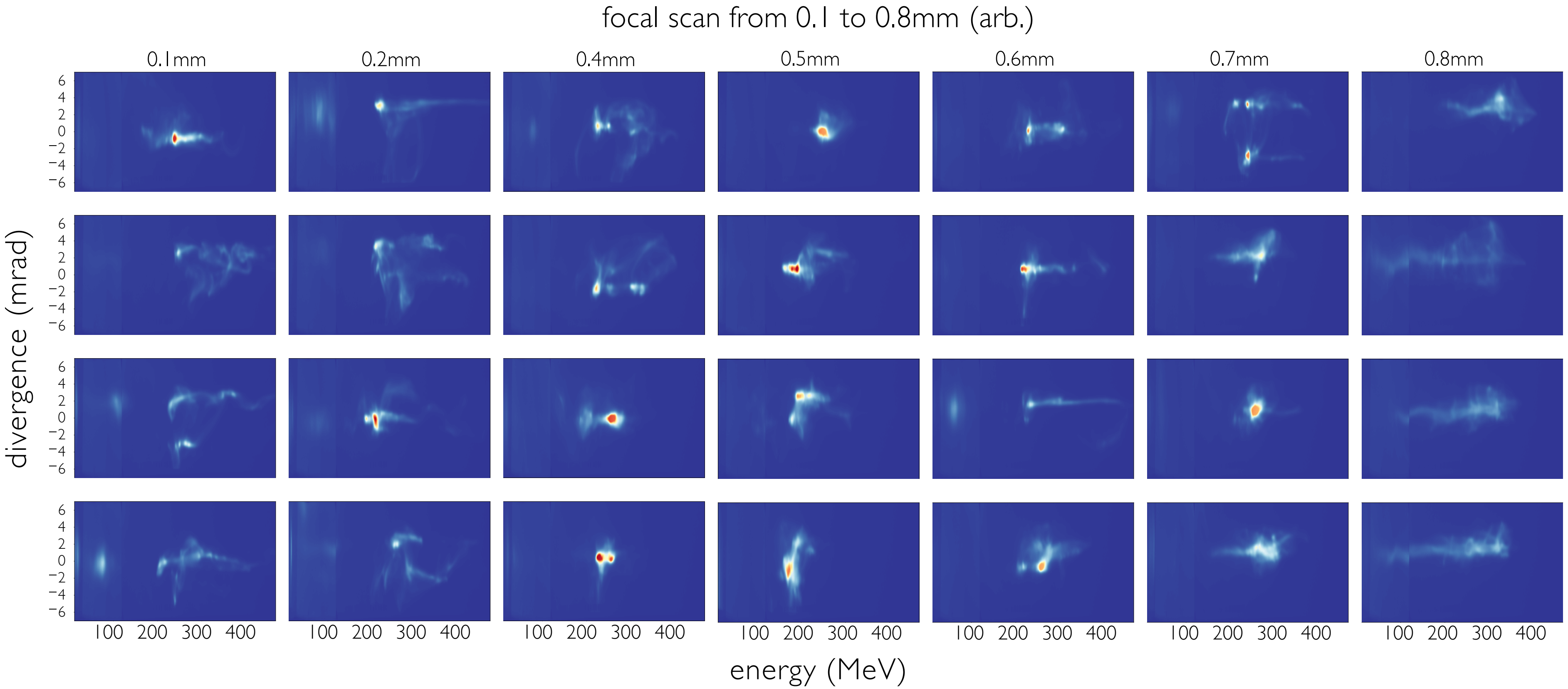
Aperture in the beam (3.1 m before target) leads to longer Rayleigh length:

~f/22 ~f/27 ~f/31



Dramatic improvement in pointing stability!

Focal spot position has strong influence on stability and pointing:



Further study with different apertures / best Strehl ratios planned

H. Ding, A. Döpp, M. Förster, M. Gilljohann, J. Götzfried, K. v. Grafenstein, F. Haberstroh, F. Irshad, G. Schilling, E. Travac, J. Wenz:

LASER-WAKEFIELD ACCELERATION: INJECTION AND BEAM LOADING

3 recent publications:

nature photonics
ARTICLES
https://doi.org/10.1038/s41566-019-0356-z

Dual-energy electron beams from a compact laser-driven accelerator

J. Wenz[1,2,7], A. Döpp[1,2,7]*, K. Khrennikov[1,2,7], S. Schindler[1,2], M. F. Gilljohann[1,2], H. Ding[1,2], J. Götzfried[1], A. Buck[1,2], J. Xu[2,6], M. Heigoldt[1,2], W. Helml[1,3,4], L. Veisz[2,5] and S. Karsch[1,2]*

PHYSICAL REVIEW X **VOL..XX,** 000000 (XXXX)

Physics of High-Charge Electron Beams in Laser-Plasma Wakefields

J. Götzfried,[1,2] A. Döpp,[1,2,*] M. F. Gilljohann,[1,2] F. M. Foerster,[1] H. Ding,[1,2] S. Schindler,[1,2] G. Schilling,[1] A. Buck,[2] L. Veisz,[2,3] and S. Karsch[1,2,†]

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PHYSICAL REVIEW X **9,** 011046 (2019)

Direct Observation of Plasma Waves and Dynamics Induced by Laser-Accelerated Electron Beams

M. F. Gilljohann,[1,2] H. Ding,[1,2] A. Döpp,[1,2,*] J. Götzfried,[1] S. Schindler,[1] G. Schilling,[1] S. Corde,[3] A. Debus,[4] T. Heinemann,[5,6] B. Hidding,[5,7] S. M. Hooker,[8] A. Irman,[4] O. Kononenko,[3] T. Kurz,[4] A. Martinez de la Ossa,[6] U. Schramm,[4] and S. Karsch[1,2,†]

Laser-wakefield acceleration (LWFA) in a nutshell

1. Ionization: A short intense laser pulse travels through a gas target and produces plasma

1. Ponderomotive expulsion: The light pressure moves plasma electrons out of the focus region, leaving behind positive space charge.

1. Wakefield generation: After the laser has passed, the displaced electrons snap back, setting up a co-moving plasma oscillation.

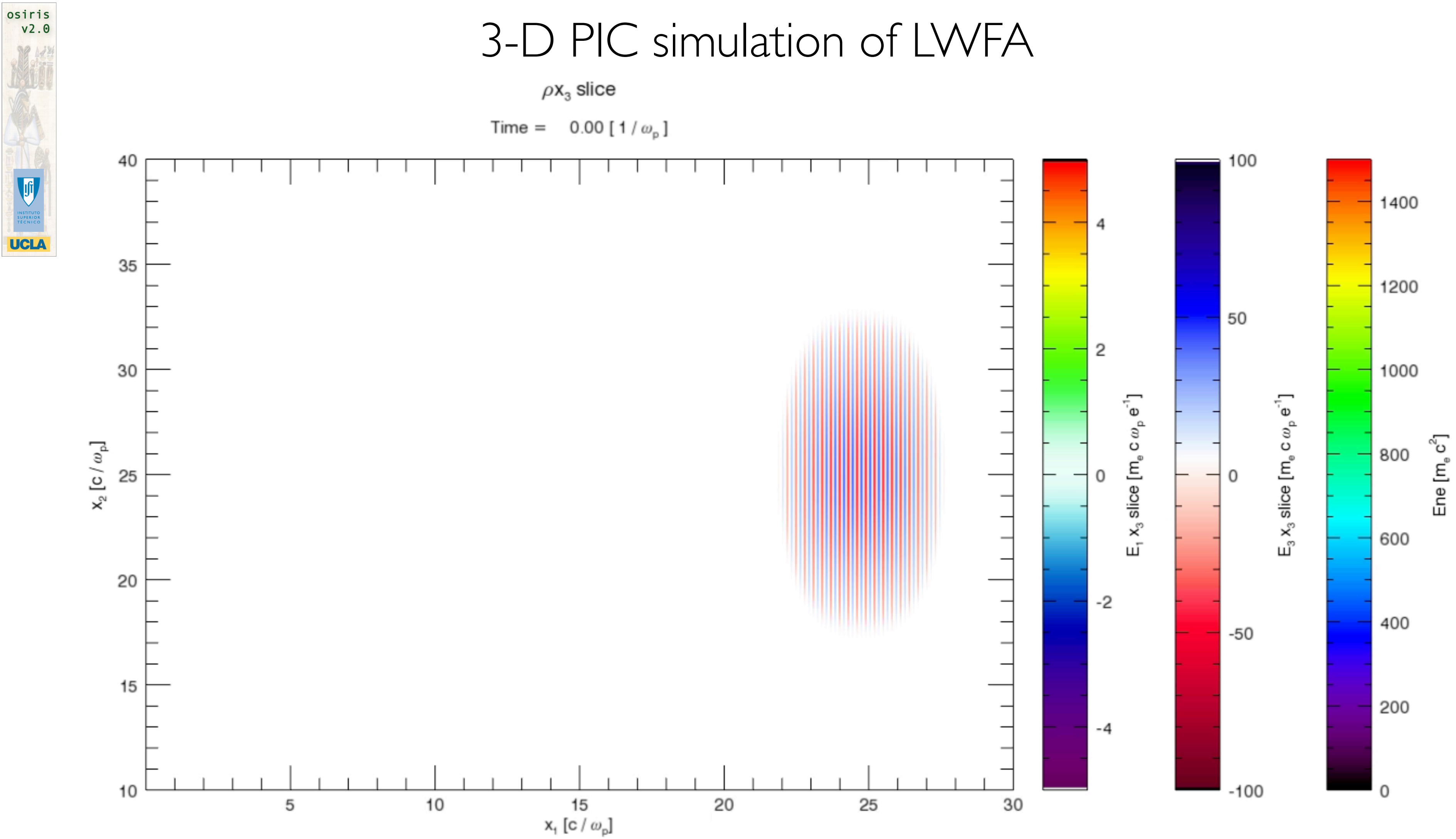
2. Injection: Some electrons have to get enough momentum to catch the wave

1. Surfing: These electrons can surf the wake and be accelerated.

Theory tools:

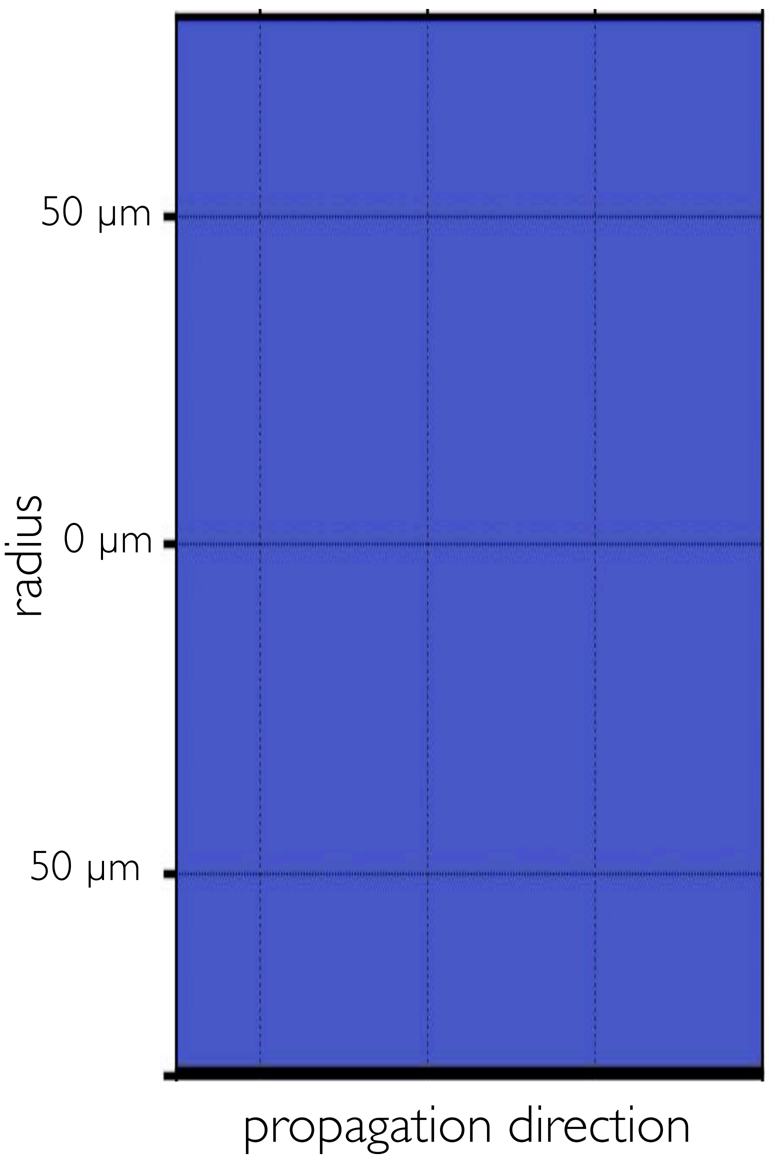
- 3-D analytical theory for linear (i.e. low-intensity) wakefields.
- 1-D fluid model (to be solved numerically) for nonlinear wakefields.
- Massively parallel Particle-in-Cell (PIC) simulations for self-consistent tracking of particles and fields in 1-D to 3-D.

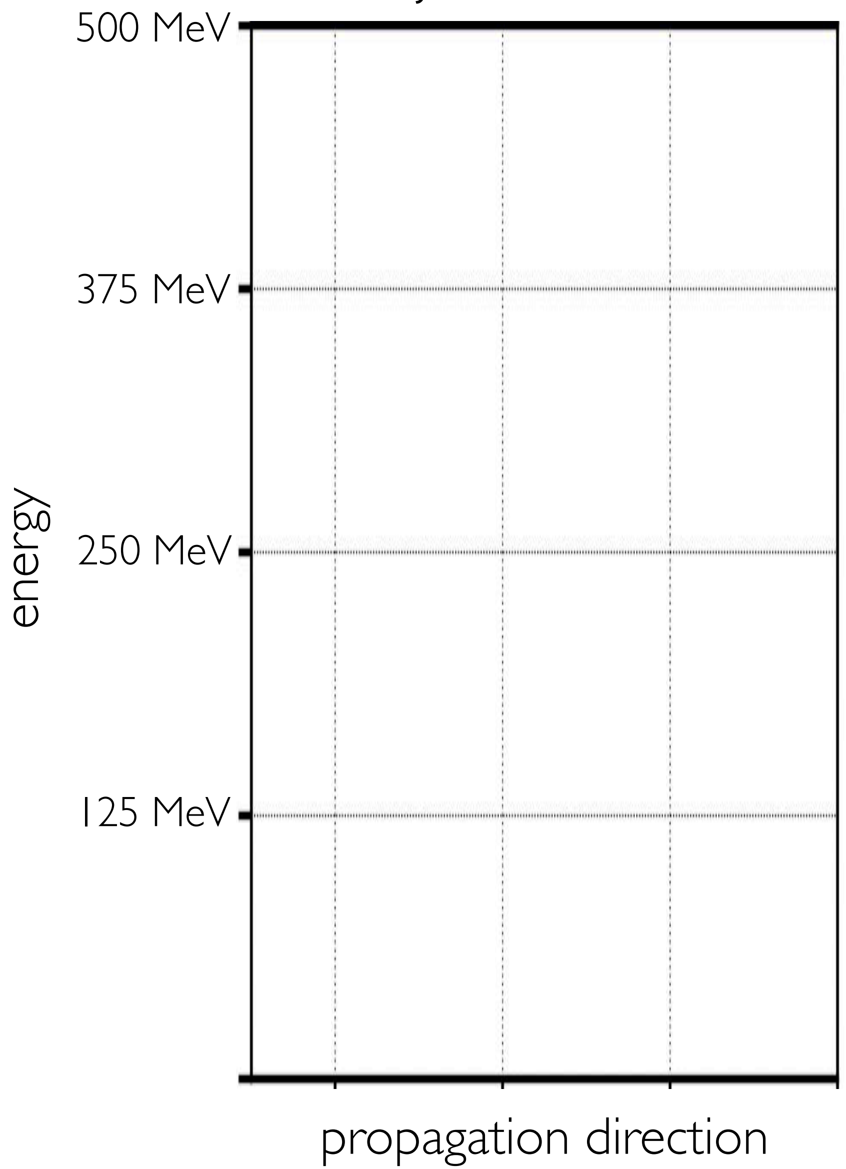
3-D PIC simulation of LWFA



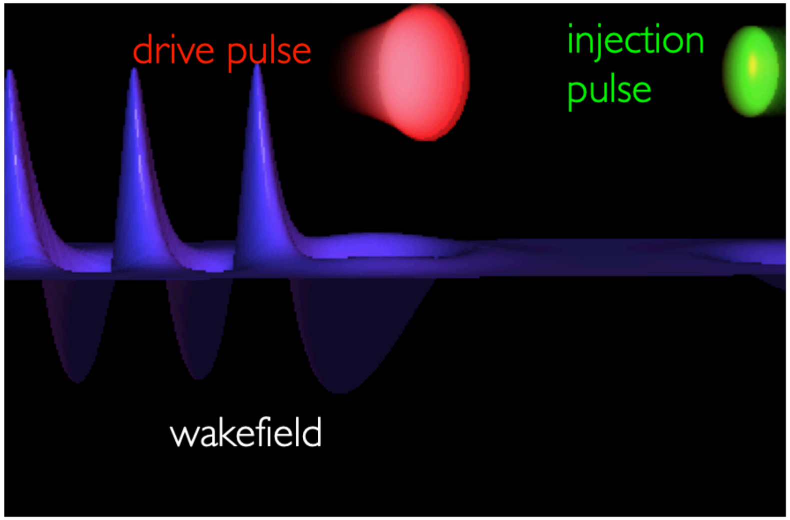
Messy, if injection is not controlled!

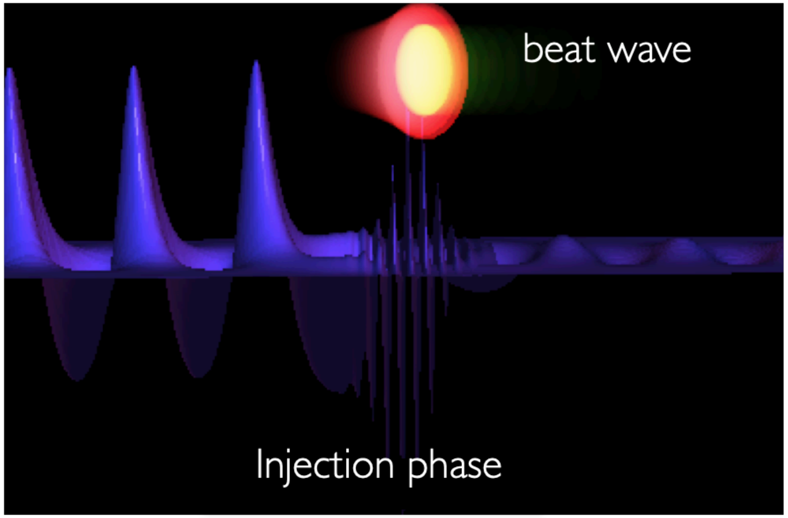
Shock-front injection: Controlled injection event





Colliding pulse injection





Images courtesy V. Malka

Two colliding pulses create a standing wave with period of λ_L

Travelling pulse: Intensity slope defining F_{pond} is given by **laser envelope**

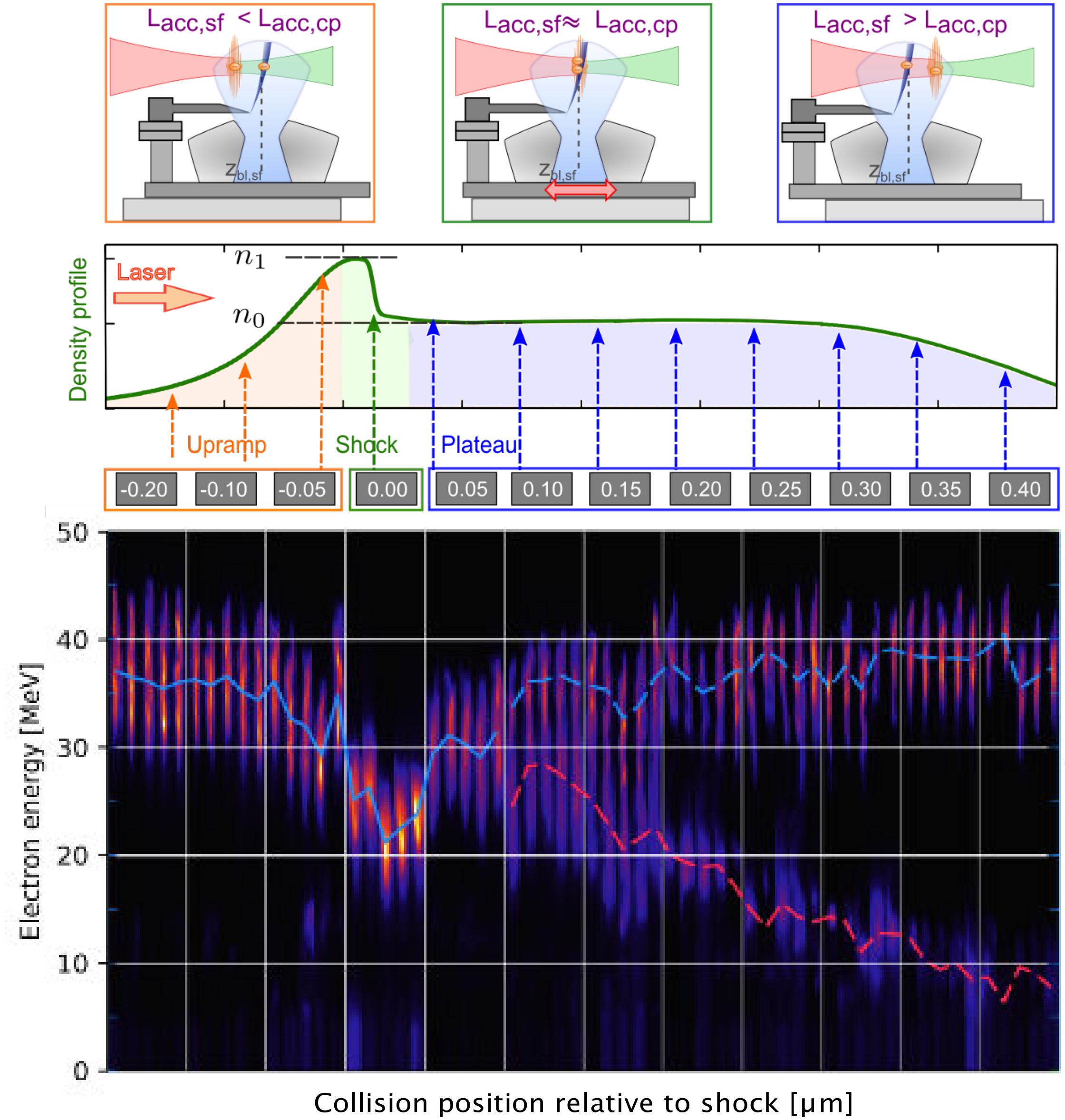
Standing wave: Intensity slope defining F_{pond} is given by **laser wavelength**

Strong ponderomotive force $F_{pond} \propto 2a_1a_2/\lambda_L$ pre-accelerates electrons only during the time the two pulses cross each other.

Images courtesy V. Malka

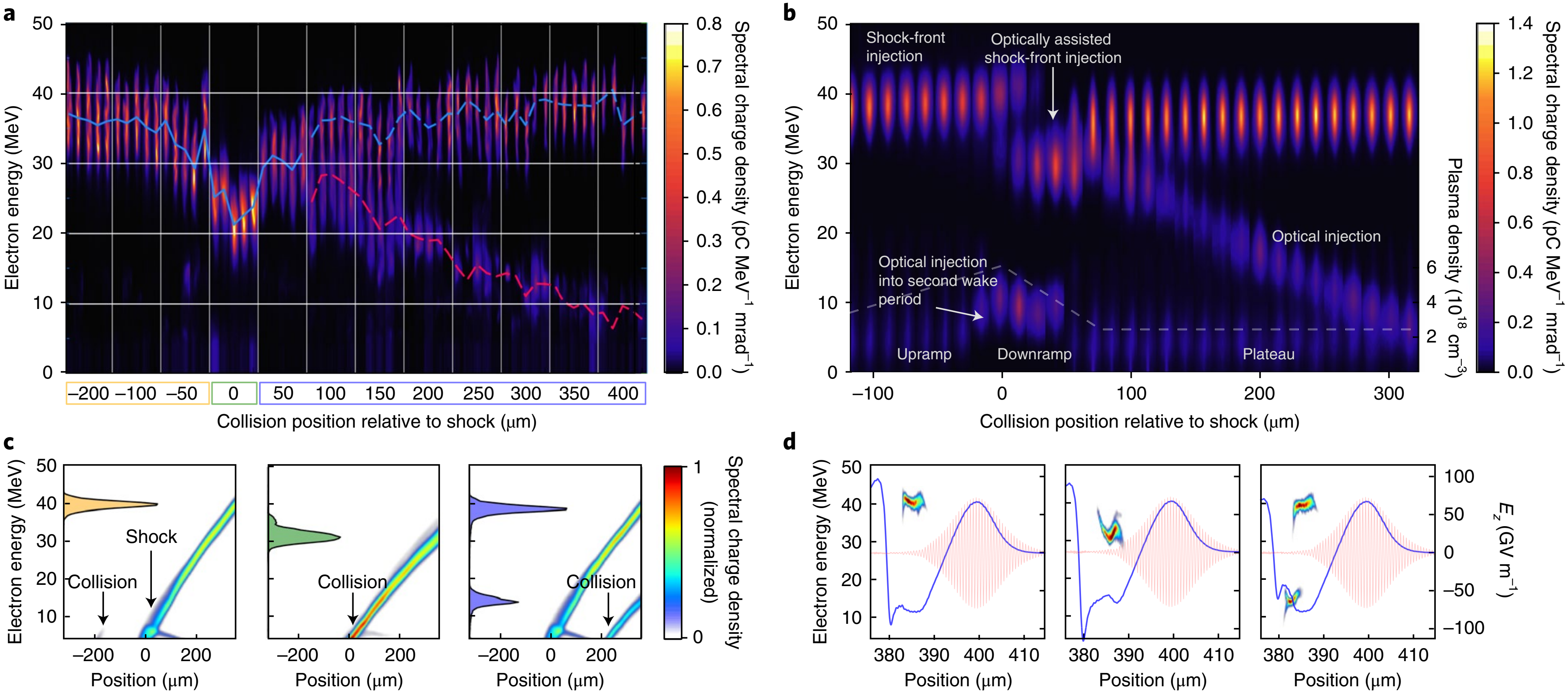
Combining shock-front and colliding pulse injection:

Dual energy electron beams from a compact laser-driven accelerator:



Wenz et al., Nature Photonics 13, 263 (2019)

Comparison with PIC simulations

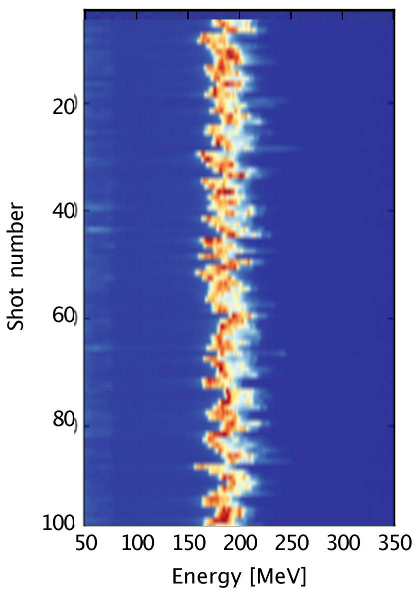


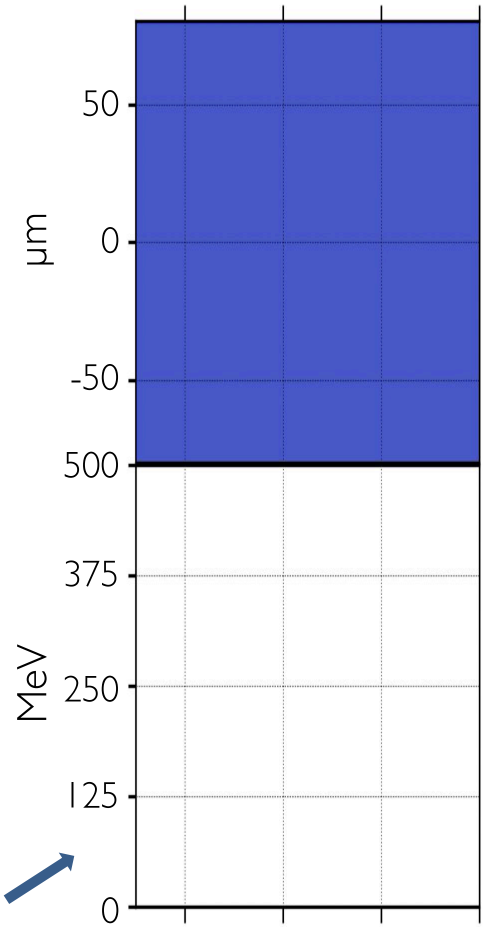
- Collision in up-ramp suppresses secondary injection
- Collision in shock enhances injected charge
- Collision after shock injects 2nd bunch

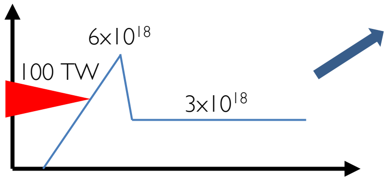
- Both bunches reside in <u>same wakefield bucket</u>

Dual energy beams from shock front injection

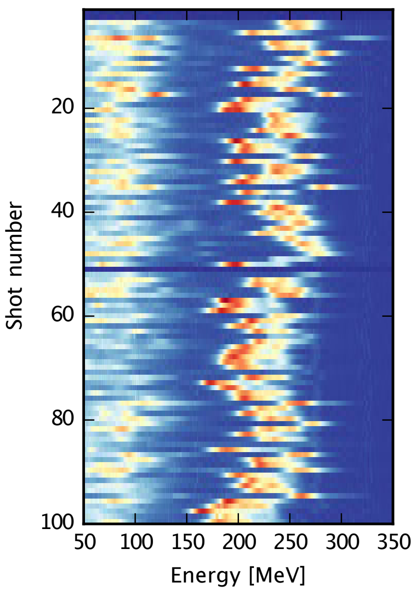
single bunch

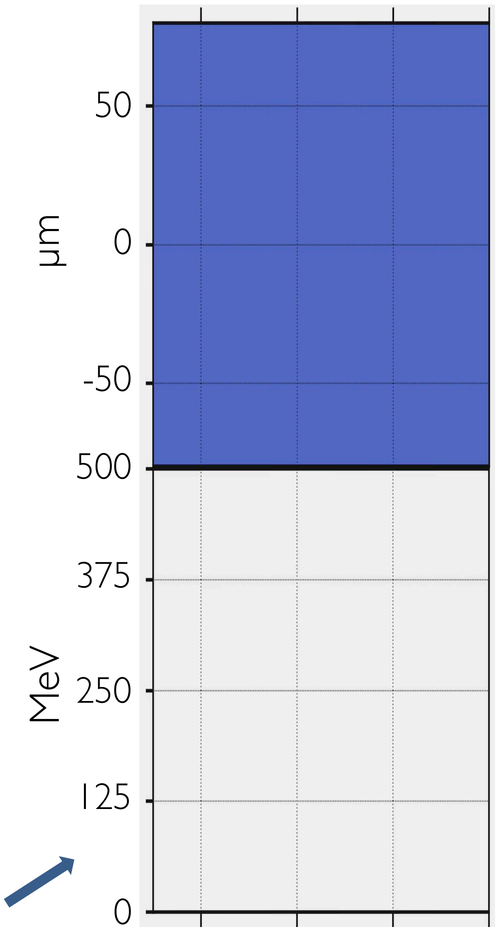


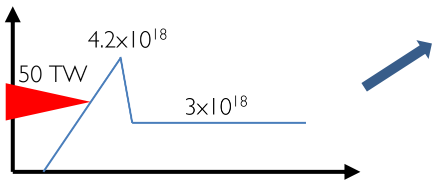




dual bunch







multiple injection into <u>different buckets</u>!

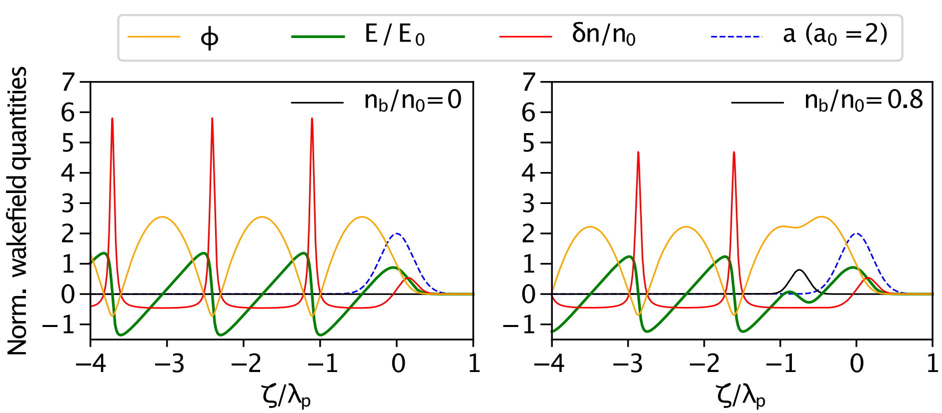
Physics of high-charge electron beams in laser-plasma wakefields

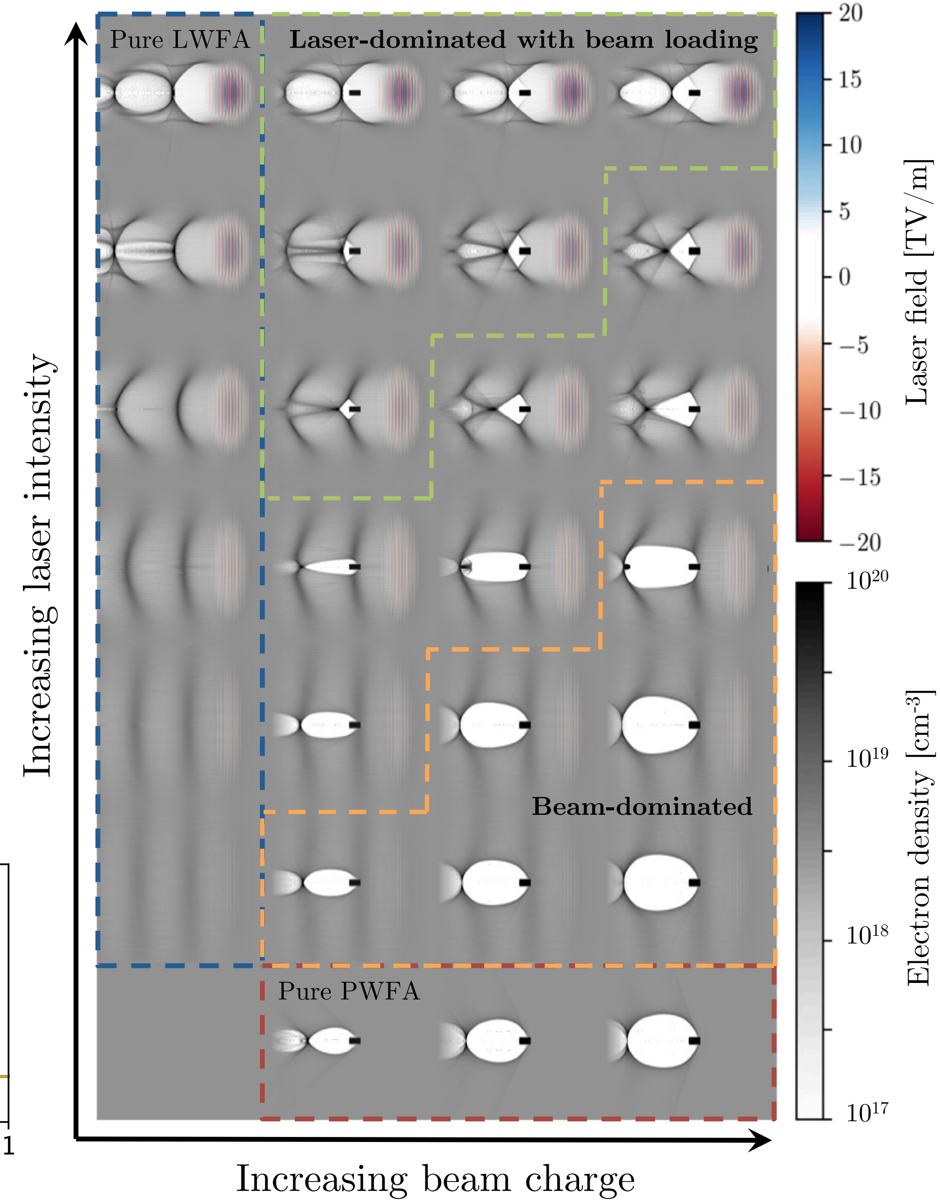
Götzfried et al, Phys. Rev. X, accepted (2020)

ATLAS-3000 allows access to high bunch charges in Laser-Wakefield Acceleration (LWFA)

↓

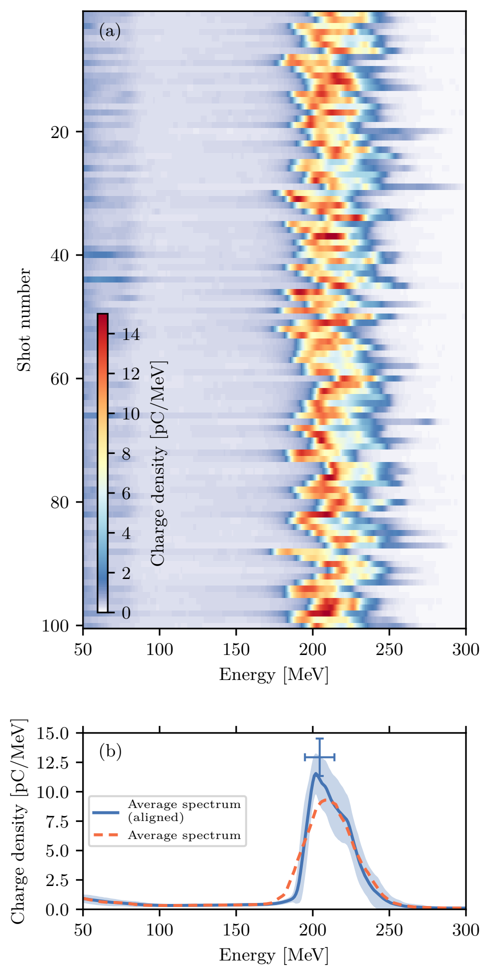
Bunch self-fields modify or dominate the laser-generated wakefield



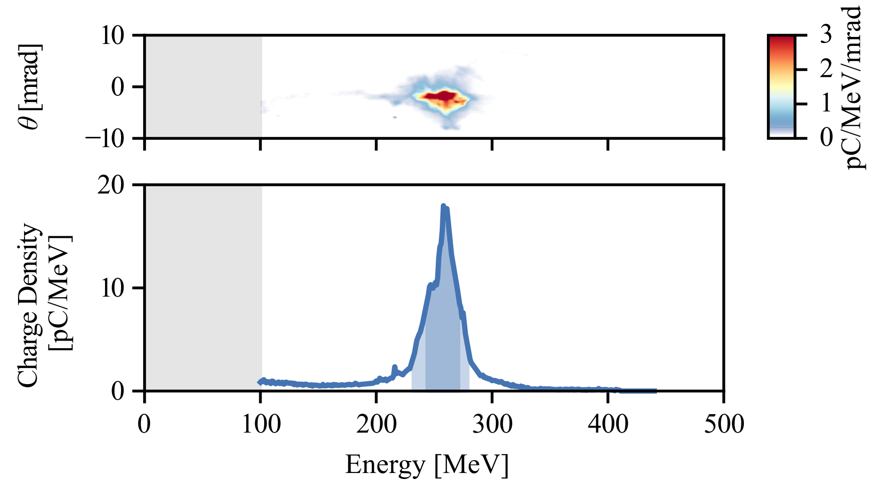


High-charge beams with different lasers:

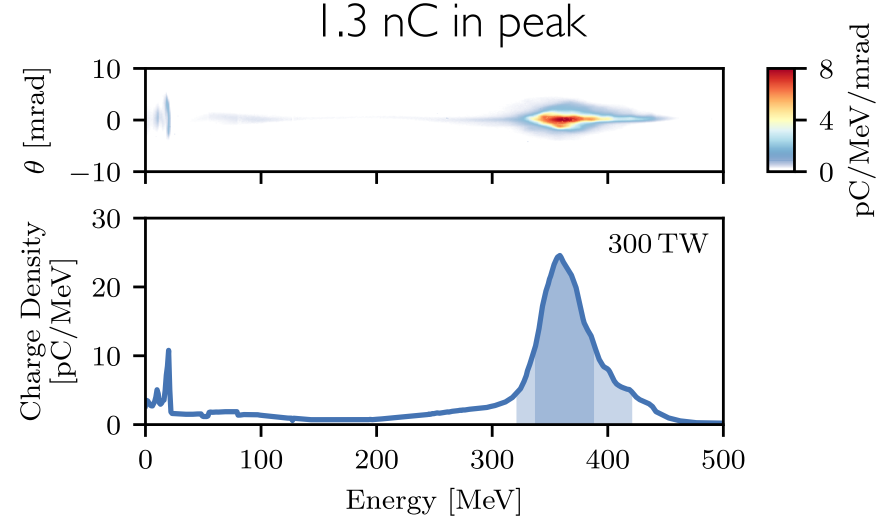
ATLAS @ LEX, 75 TW:
330 pC in peak



ATLAS @ LEX, 110 TW:
473 pC in peak



ATLAS-3000 @ CALA, 300 TW:
1.3 nC in peak

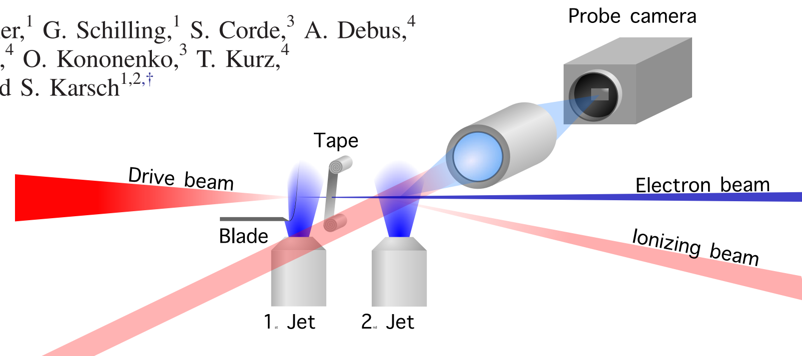


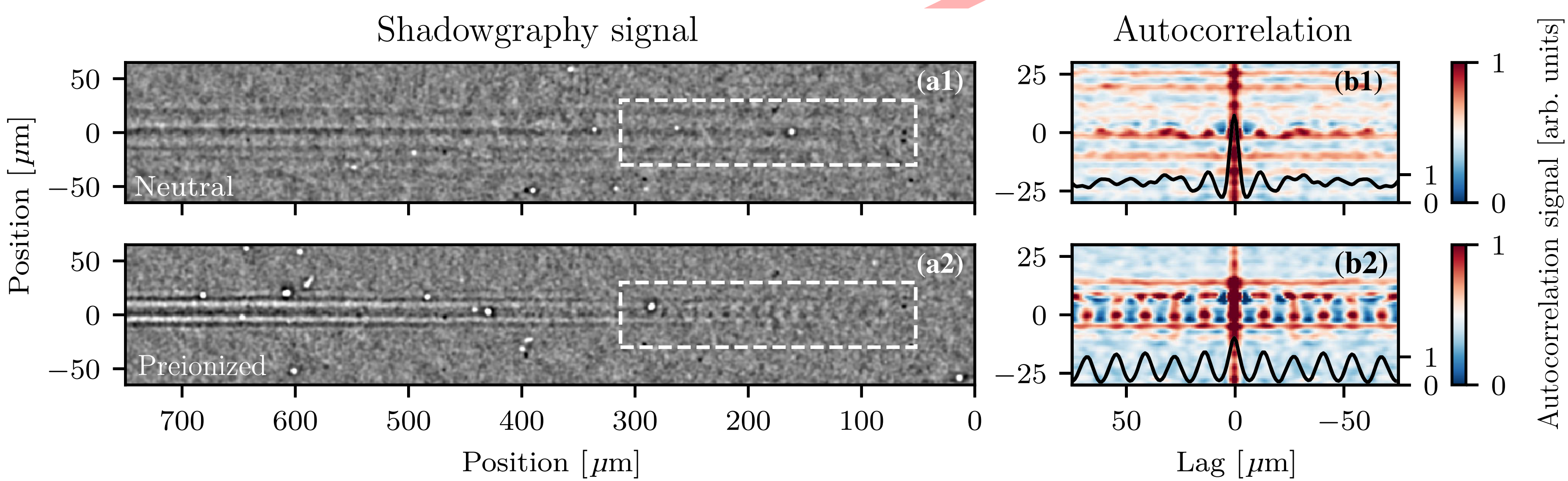
High-charge bunches drive wakefields in plasma:

PHYSICAL REVIEW X **9,** 011046 (2019)

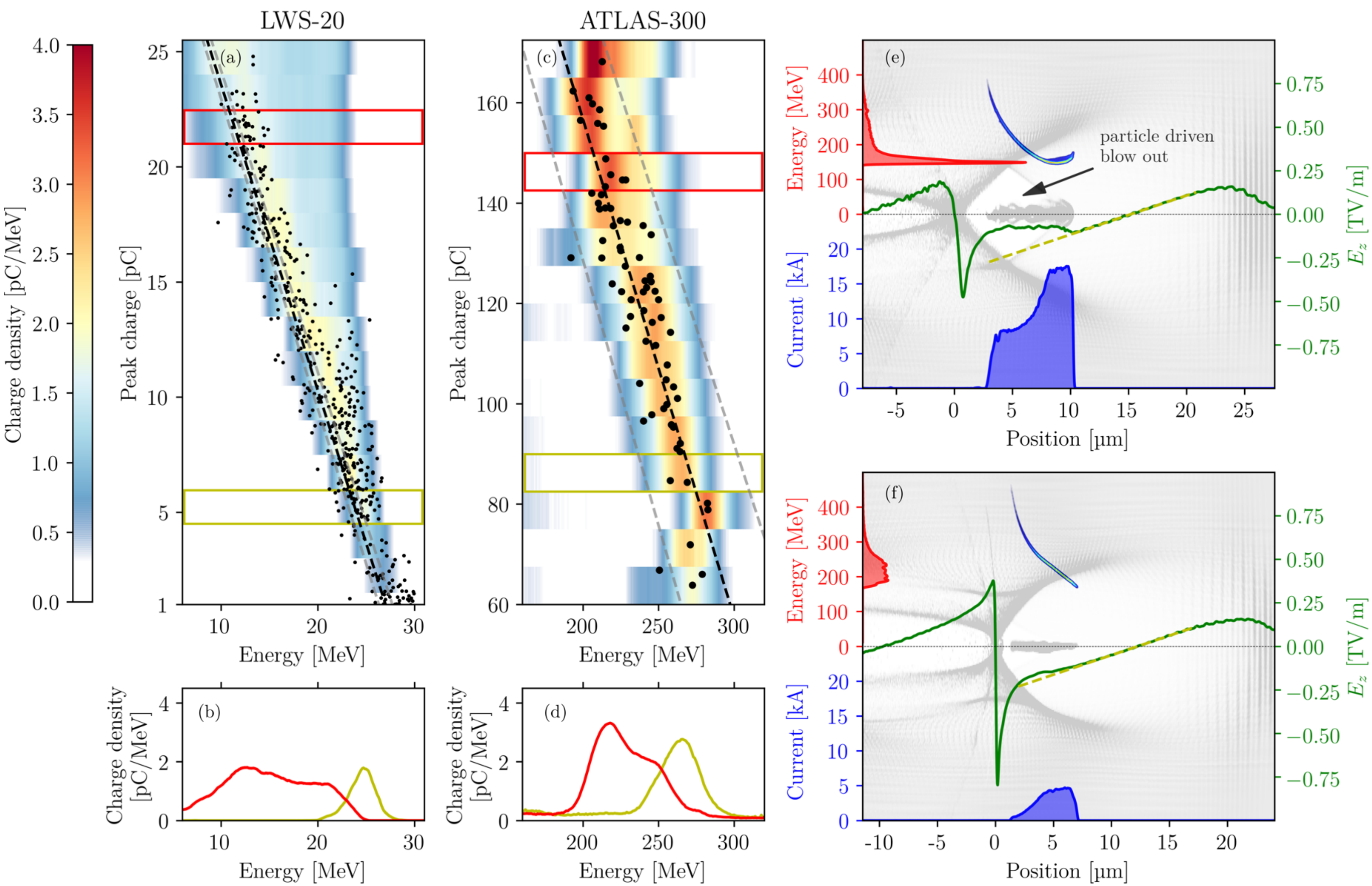
Direct Observation of Plasma Waves and Dynamics Induced by Laser-Accelerated Electron Beams

M. F. Gilljohann,[1,2] H. Ding,[1,2] A. Döpp,[1,2,*] J. Götzfried,[1] S. Schindler,[1] G. Schilling,[1] S. Corde,[3] A. Debus,[4] T. Heinemann,[5,6] B. Hidding,[5,7] S. M. Hooker,[8] A. Irman,[4] O. Kononenko,[3] T. Kurz,[4] A. Martinez de la Ossa,[6] U. Schramm,[4] and S. Karsch[1,2,†]

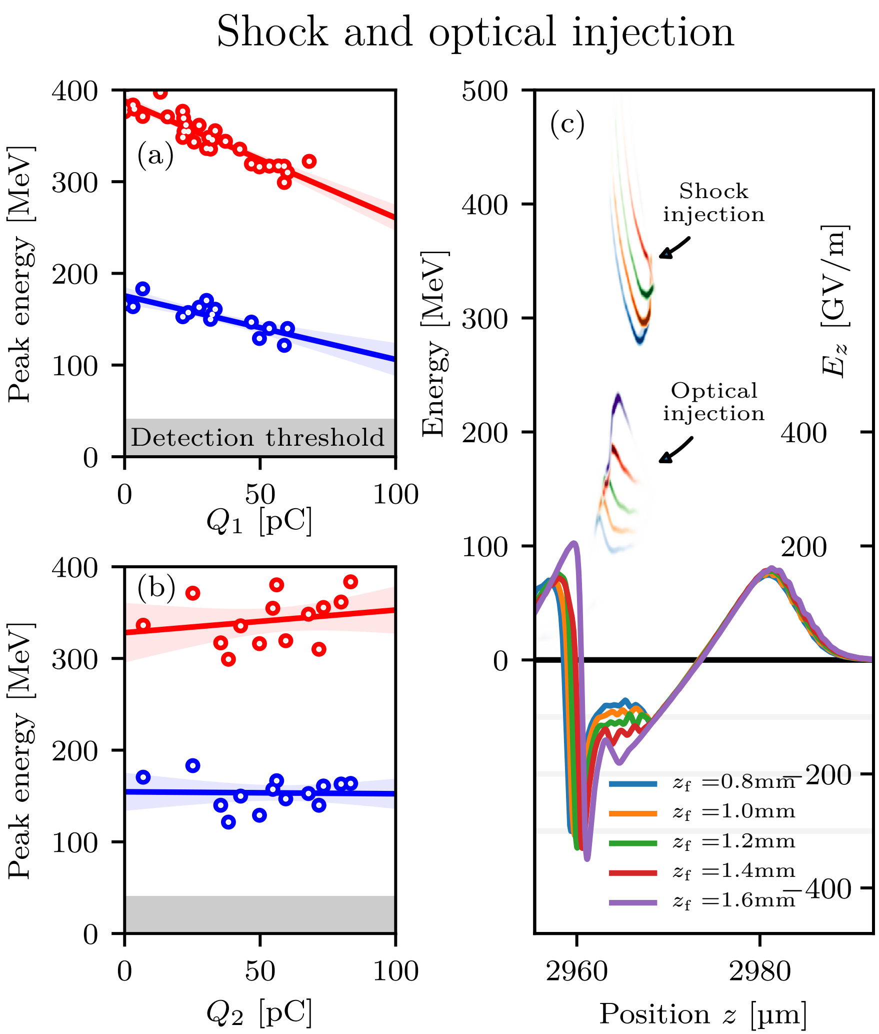




Beam loading: Spectral downshift at high bunch charge



Probing beam loading with secondary injected bunches:



Two bunches in the **same bucket**, 2nd probes the **same** wakefield bucket.

- Top left: Energy of 1st and 2nd bunch against charge of the 1st:
  ⇒ Beamloading in both bunches

- Bottom left: Energy of 1st and 2nd bunch against charge of the 2nd:
  ⇒ no beamloading effects depending on the charge of the 2nd bunch.

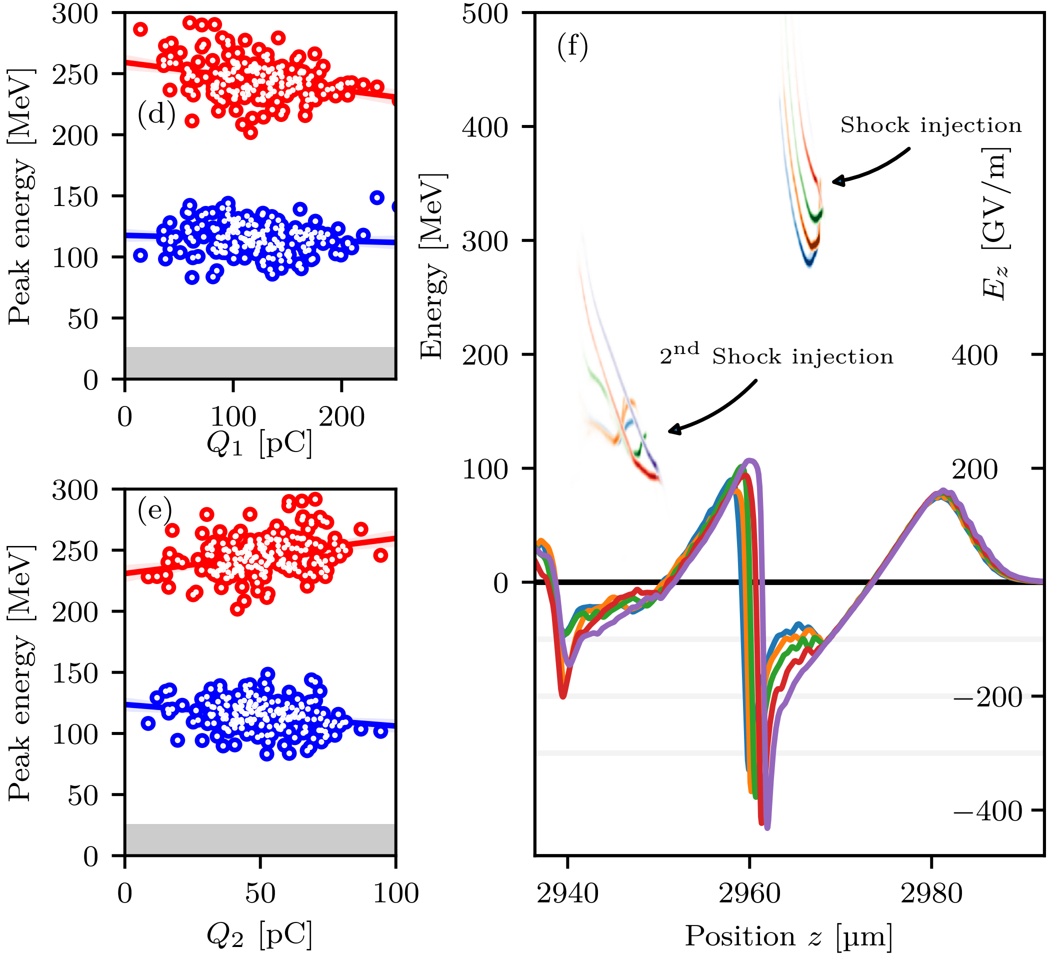
Probing beam loading with secondary injected bunches:

Two bunches in **two consecutive buckets:** 2nd probes **next** wakefield bucket

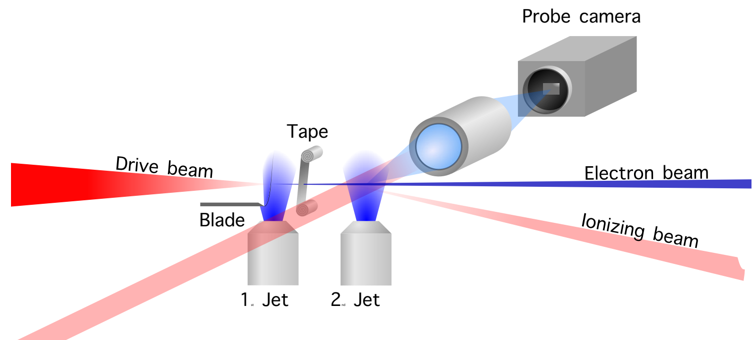
- Top left: Energy of 1st and 2nd bunch against charge of the 1st:
  ⇒ Beamloading of the 1st, no effect on 2nd.

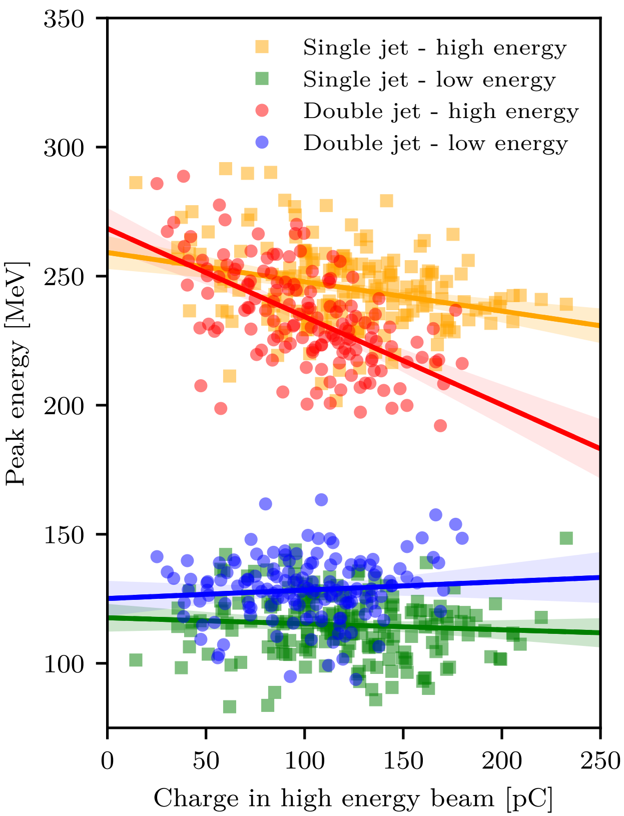
- Energy of 1st and 2nd bunch against charge of the 2nd:
  ⇒ high charge in 2nd bucket reduces charge in the 1st, less beamloading in the 1st with more charge in the 2nd.

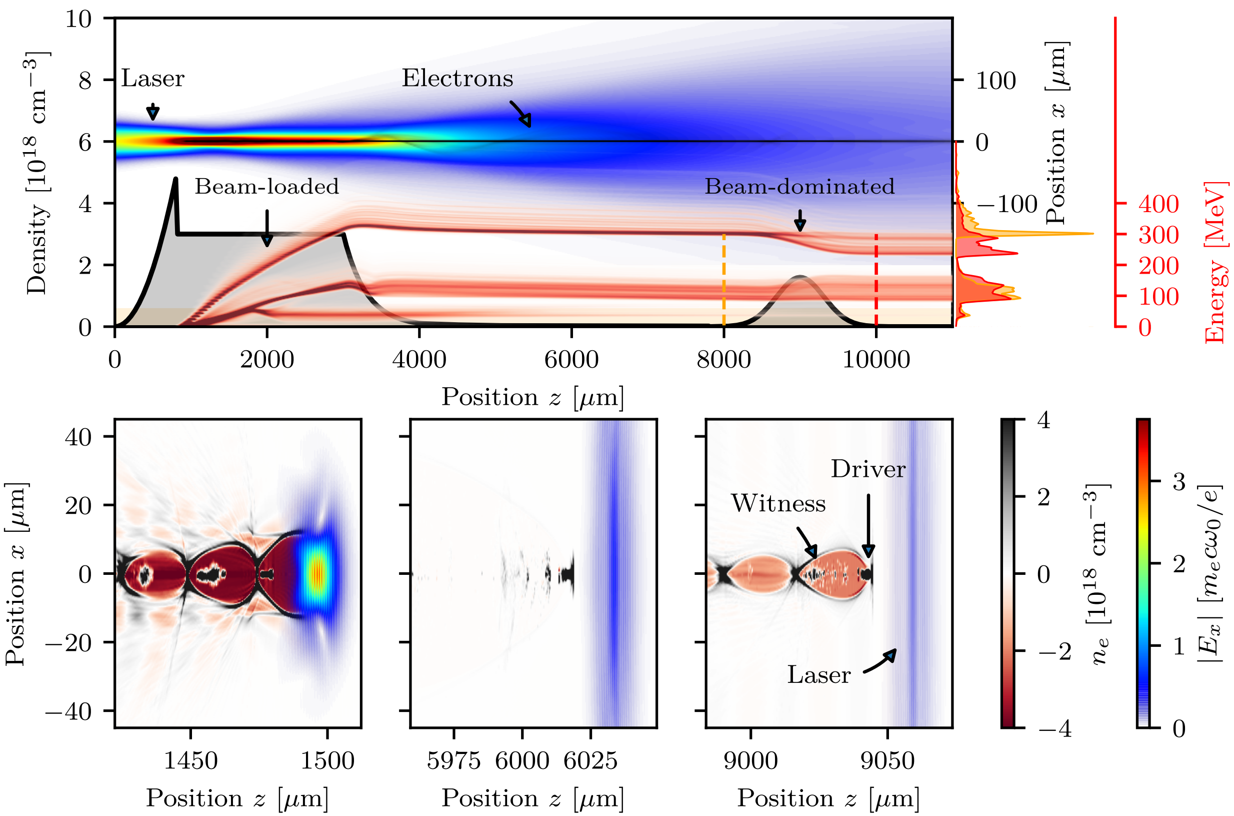
Shock injection



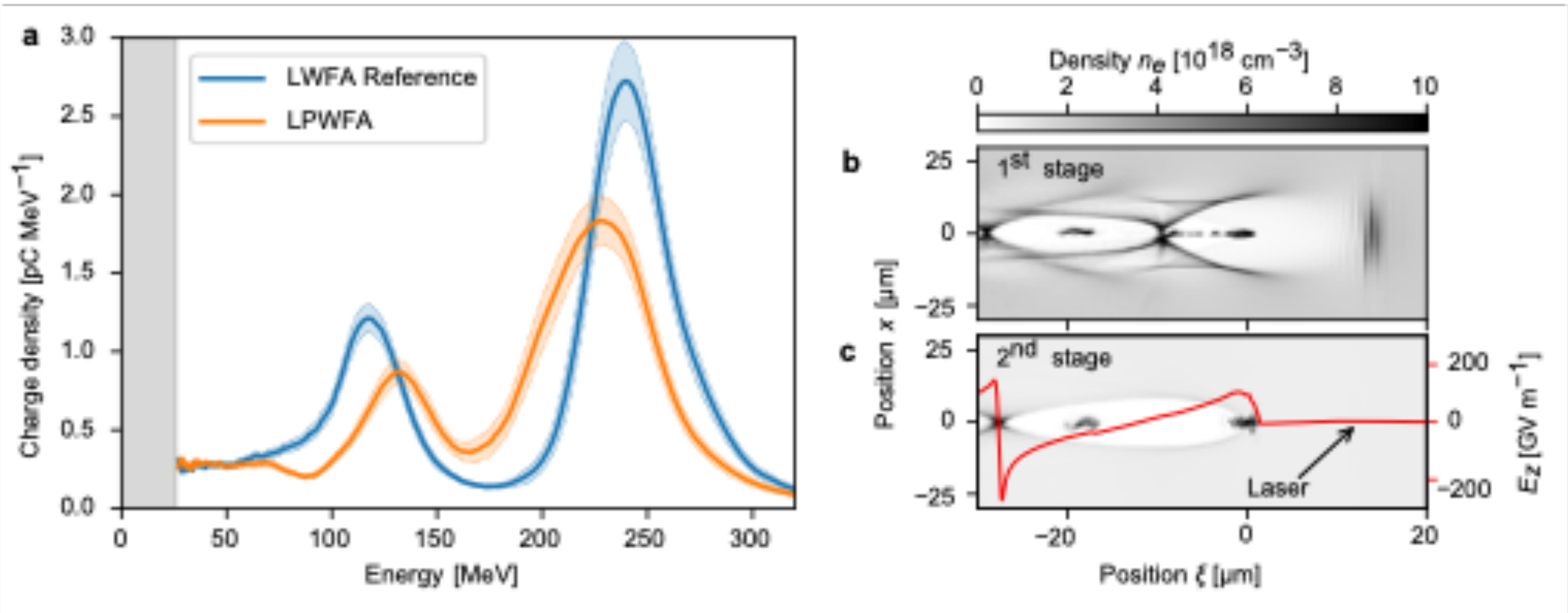
Beam-domianted case: charge-dependent acceleration of a witness bunch in beam-driven wakefield







Overall effect: externally injected, LWFA-driven PWFA (hybrid accelerator)



- Drive bunch loses energy to set up a plasma wave, witness bunch gains energy.
- Energy gain increases for higher density in PWFA stage, but then spectral peaks start to overlap.
- Witness capture efficiency approx. 70%

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Technische Universität München

Center for Advanced Laser Applications

CALA

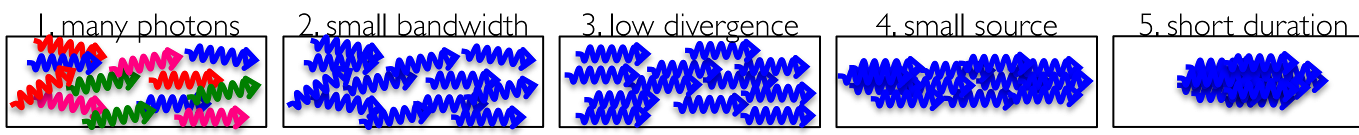
Why do we do this?

$$\text{Brilliance} = \frac{\text{photons}}{\boxed{\text{mm}^2 \cdot \text{mrad}^2} \cdot \boxed{\text{s} \cdot 0.1\% \text{ bandwidth}}}$$

transv. emittance (=phase space area)

long. emittance

Small emittance electron beams are necessary for high X-ray brilliance:



That's where LWFA sources excel

Hybrid acceleration can provide emittance figures orders of magnitude below conventional LWFA:

PRL 111, 245003(2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

High-Quality Electron Beams from Beam-Driven Plasma Accelerators by Wakefield-Induced Ionization Injection

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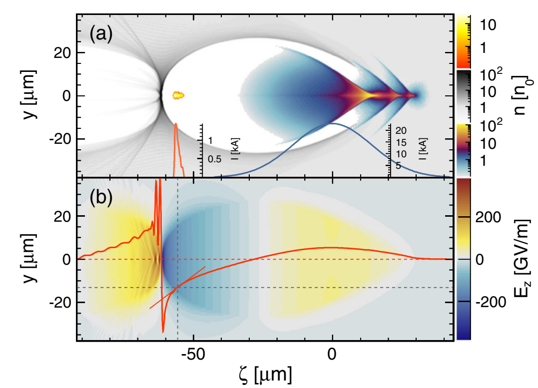

Credits:

WG Karsch:

Postdoc:

A. Döpp

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- H. Ding
- S. Schindler
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…and the whole CALA team…

Nick, Olli, Flo, Hans, Martin, Johannes…