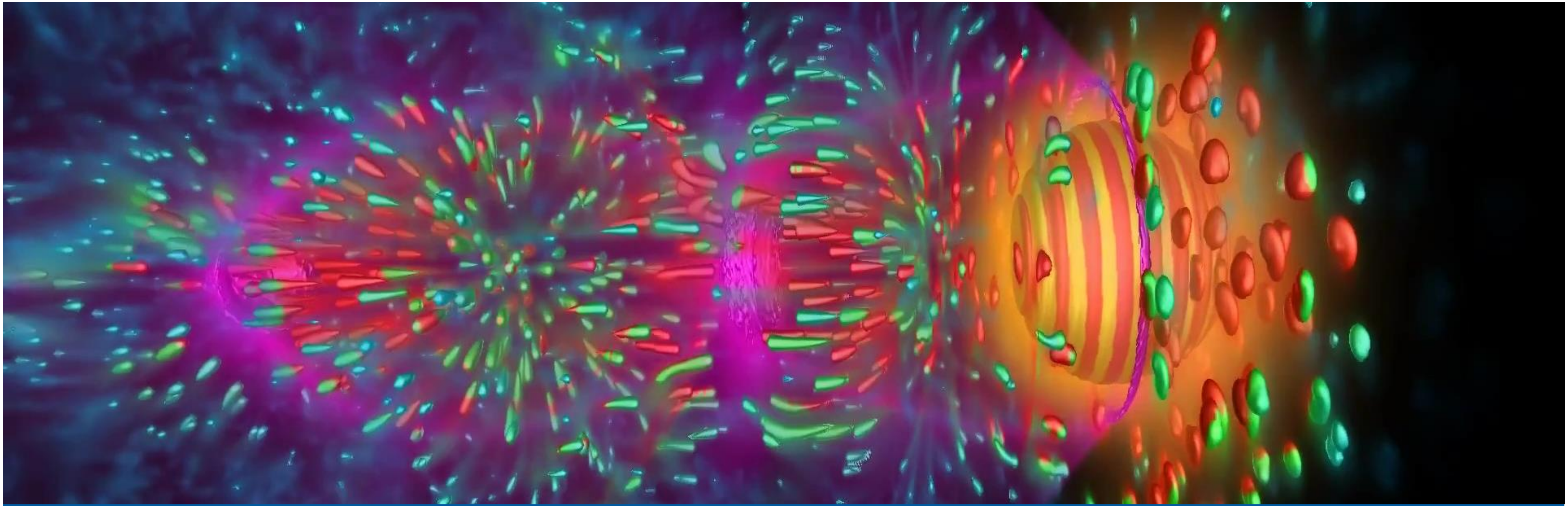

Accompanying the hybrid LPWFA experiment campaign with a computer simulation campaign

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Accompanying the hybrid LPWFA experiment campaign with a computer simulation campaign

What we model, what we learn, and where we need to become better

K. Steiniger, R. Pausch, S. Bastrakov, Y. Y. Chang, J. P. Couperus Cabadağ, A. Irman, A. Köhler, T. Kurz, S. Schöbel, R. Widera, U. Schramm, O. Zarini & A. Debus – *HZDR*

M. Bussmann – *CASUS*

T. Heinemann, R. W. Assmann & A. Martinez de la Ossa – *DESY*

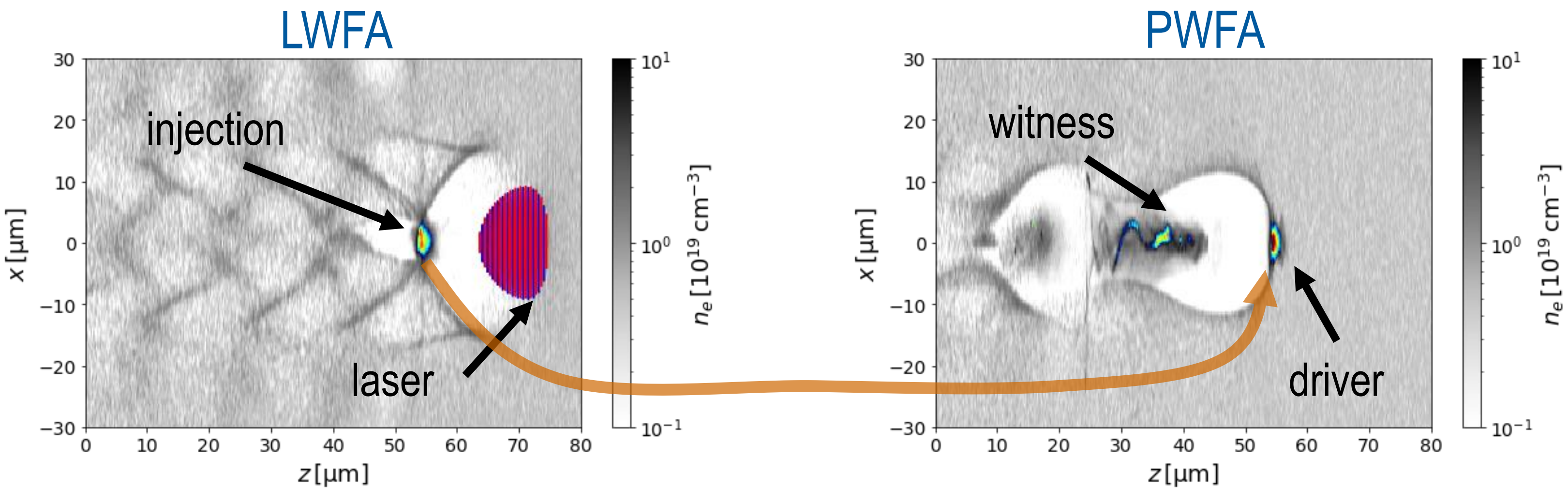
T. Heinemann, B. Hidding – *University of Strathclyde, The Cockcroft Institute*

M. F. Gilljohann, H. Ding, J. Götzfried, S. Schindler, A. Döpp & S. Karsch – *LMU Munich, MPQ*

O. Kononenko, G. Raj & S. Corde – *LOA*

Combining LWFA and PWFA

A compact source for high brightness electron beams



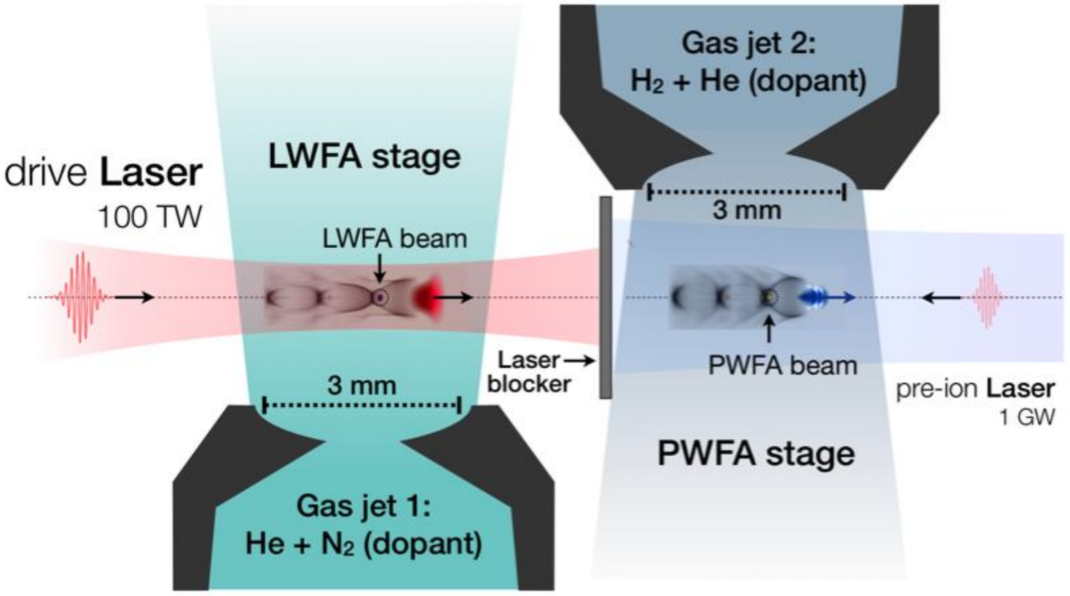
Combine both to build a compact PWFA accelerator

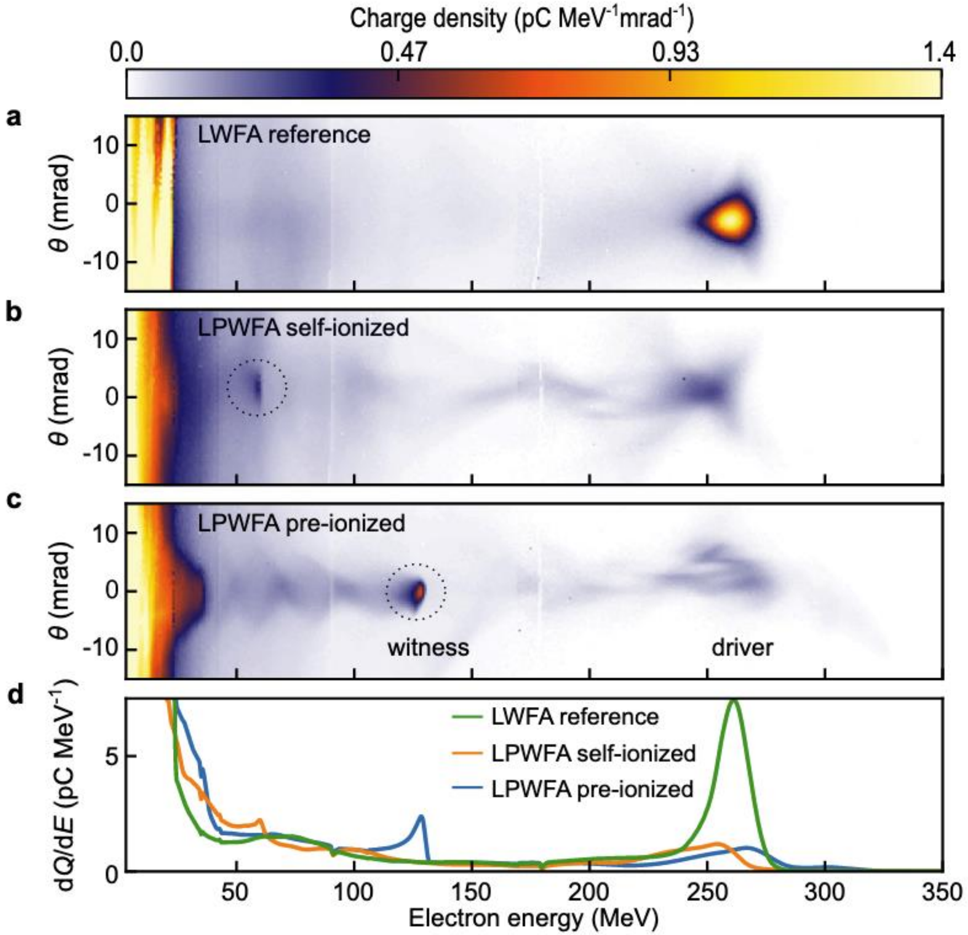
- driven by high-power laser pulse
- compact, laboratory-sized
- provides high-current electron beam

- driven by high-current beam
- km-sized facilities (FACET SLAC)
- capable of producing high-brightness witness beams

First demonstration of LPWFA by Hybrid collaboration

Observation of accelerated witness electron bunches





nature COMMUNICATIONS

ARTICLE

Check for updates

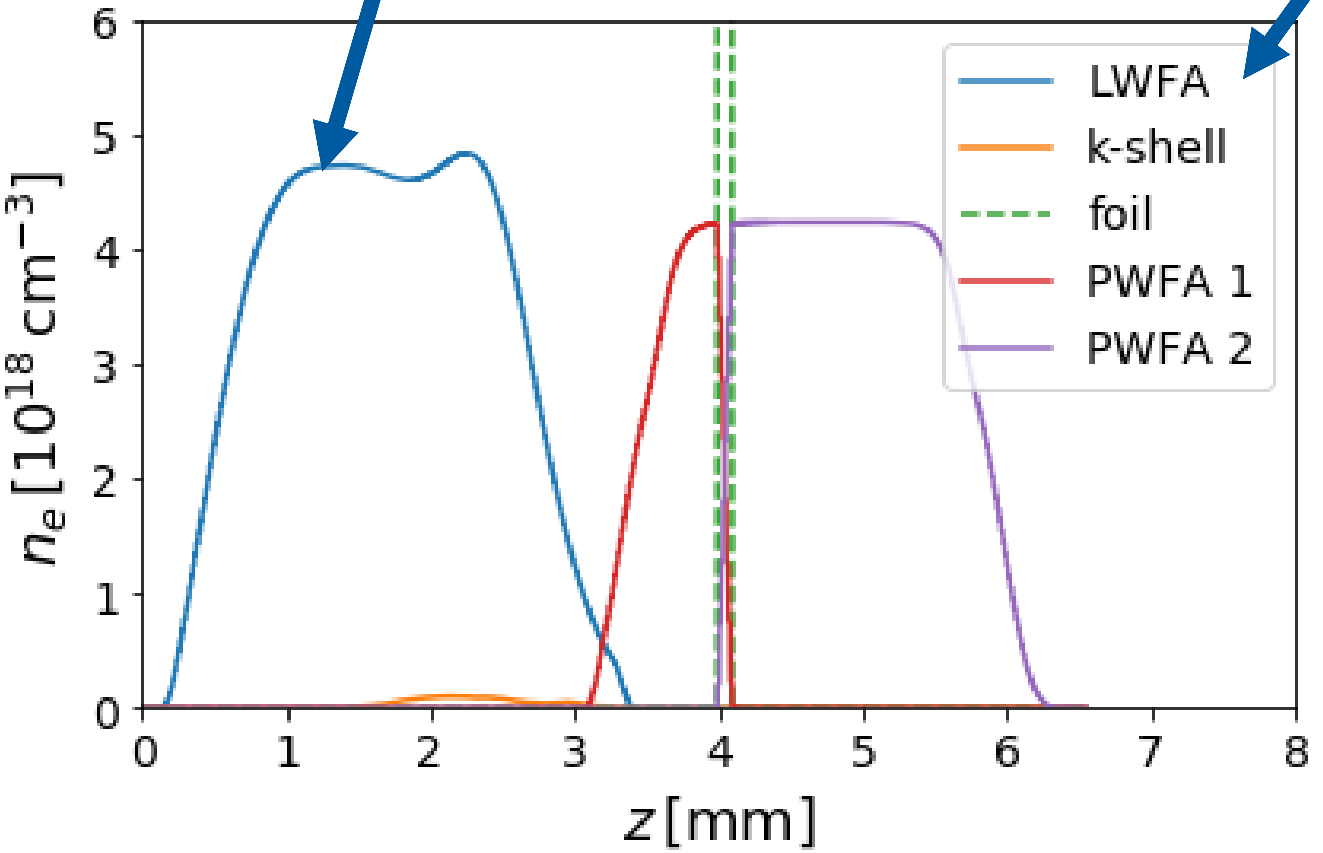
https://doi.org/10.1038/s41467-021-23000-7 OPEN

Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams

T. Kurz[1,2,10✉], T. Heinemann[3,4,5,10], M. F. Gilljohann[6,7], Y. Y. Chang[1], J. P. Couperus Cabadağ[1], A. Debus[1], O. Kononenko[8], R. Pausch[1], S. Schöbel[1,2], R. W. Assmann[3], M. Bussmann[1,9], H. Ding[6,7], J. Götzfried[6,7], A. Köhler[1], G. Raj[8], S. Schindler[6,7], K. Steiniger[1], O. Zarini[1], S. Corde[8], A. Döpp[6,7], B. Hidding[4,5], S. Karsch[6,7✉], U. Schramm[1,2], A. Martinez de la Ossa[3] & A. Irman[1✉]

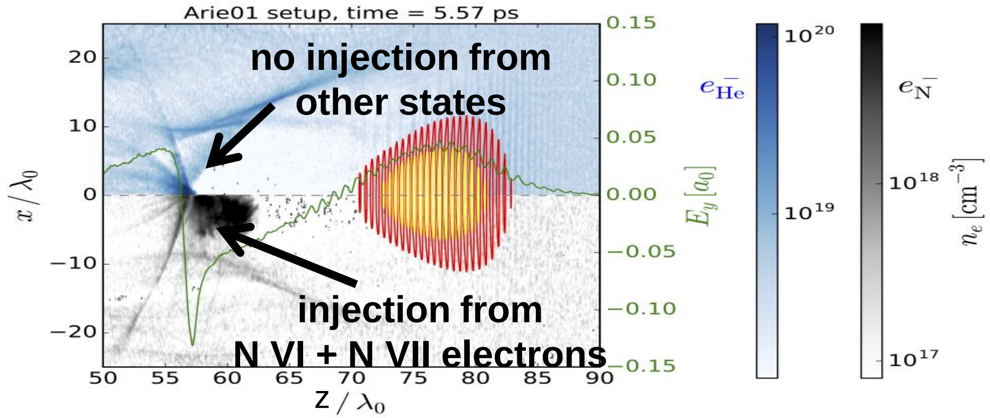
What we started out with...

Gas profile as measured in experiment



Different electron 'species' in the simulation to disentangle dynamics of

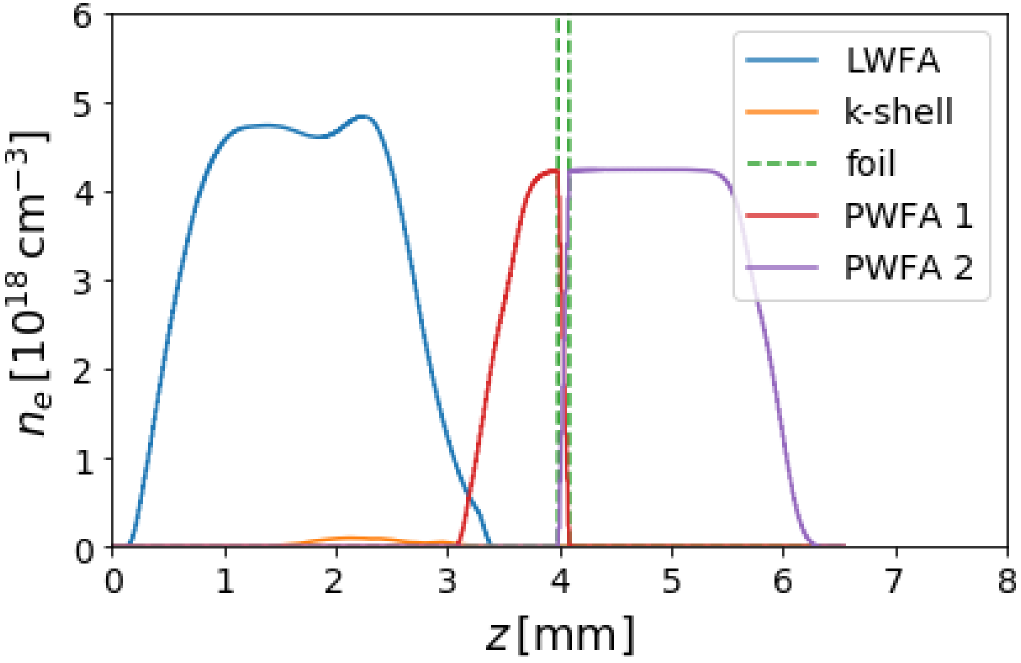
- LWFA stage (Spatially truncated ionization injection)
  - (preionized) background electrons
  - ionized electrons



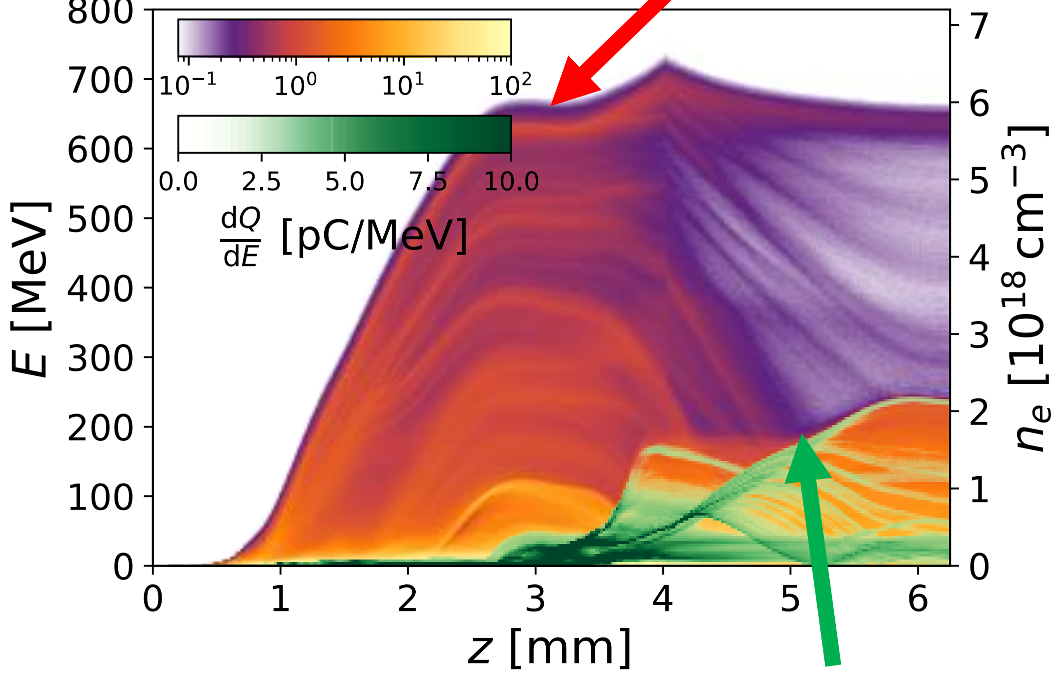
- PWFA stage
  - upramp
  - foil
  - plateau

What we started out with...

...was not great, but we observed witness generation and could locate its origin



2.7 J laser energy



Driver energy too high (expect ~300MeV)

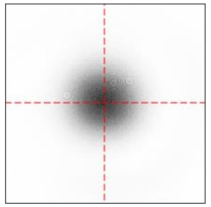
Stable witness acceleration

Laser modelling is key to improve LWFA stage predictions

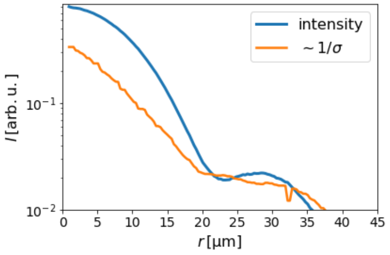
1. Correct for real laser energy ← there was a degraded optical component causing energy decrease
2. Incorporate the measured intensity profile → It has a strong impact on electron injection

- intensity profile along propagation reveals structured laser profile
- fit to Gauss-Laguerre description to include in particle-in-cell simulation

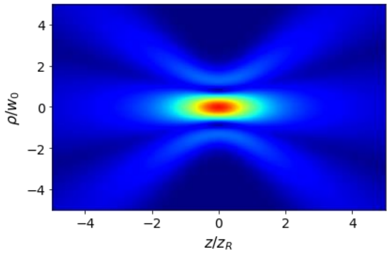
measured profile

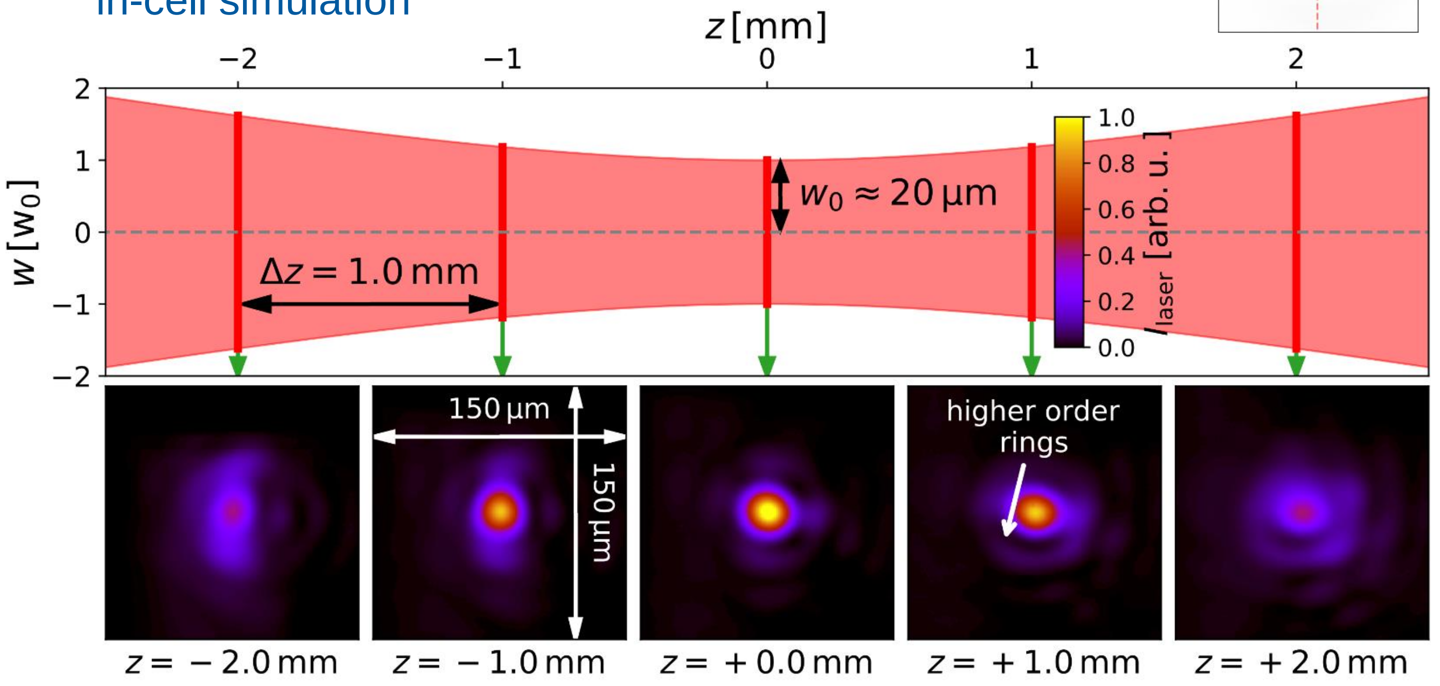


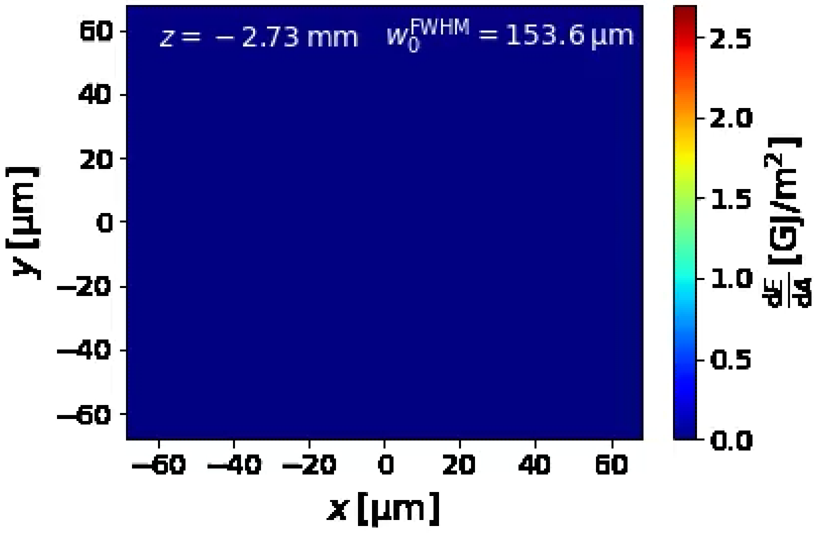
fit of radial components



full transversal laser evolution in PIConGPU







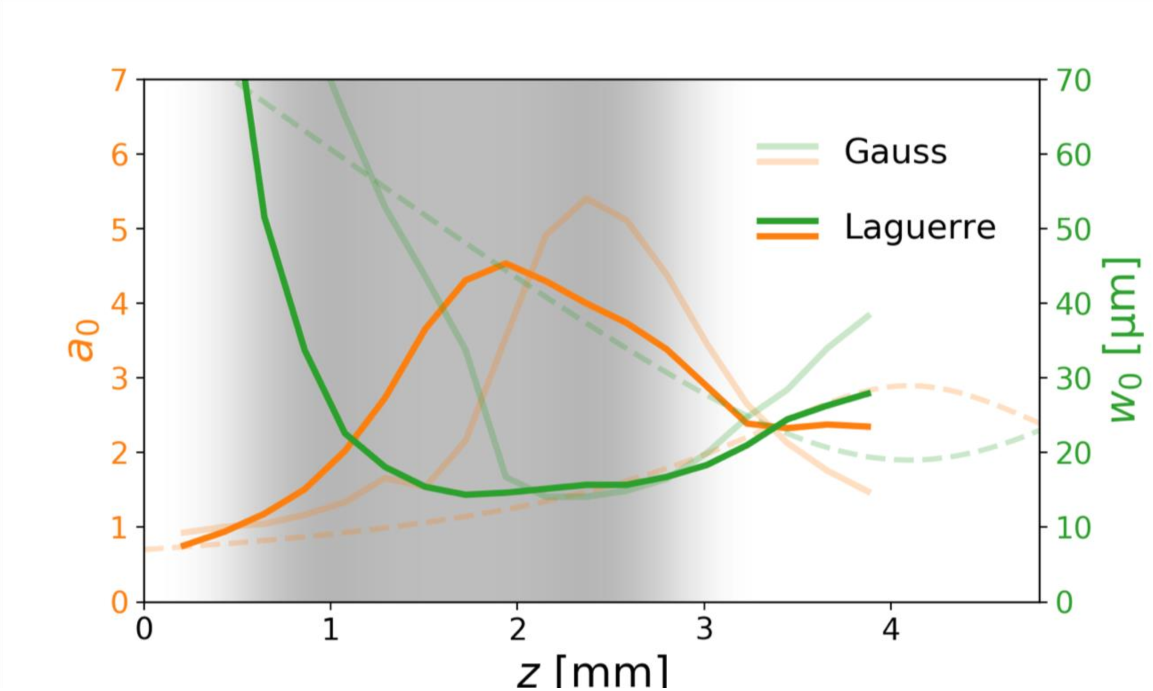
PIConGPU DRESDEN concept SCIENCE AND INNOVATION CAMPUS HZDR

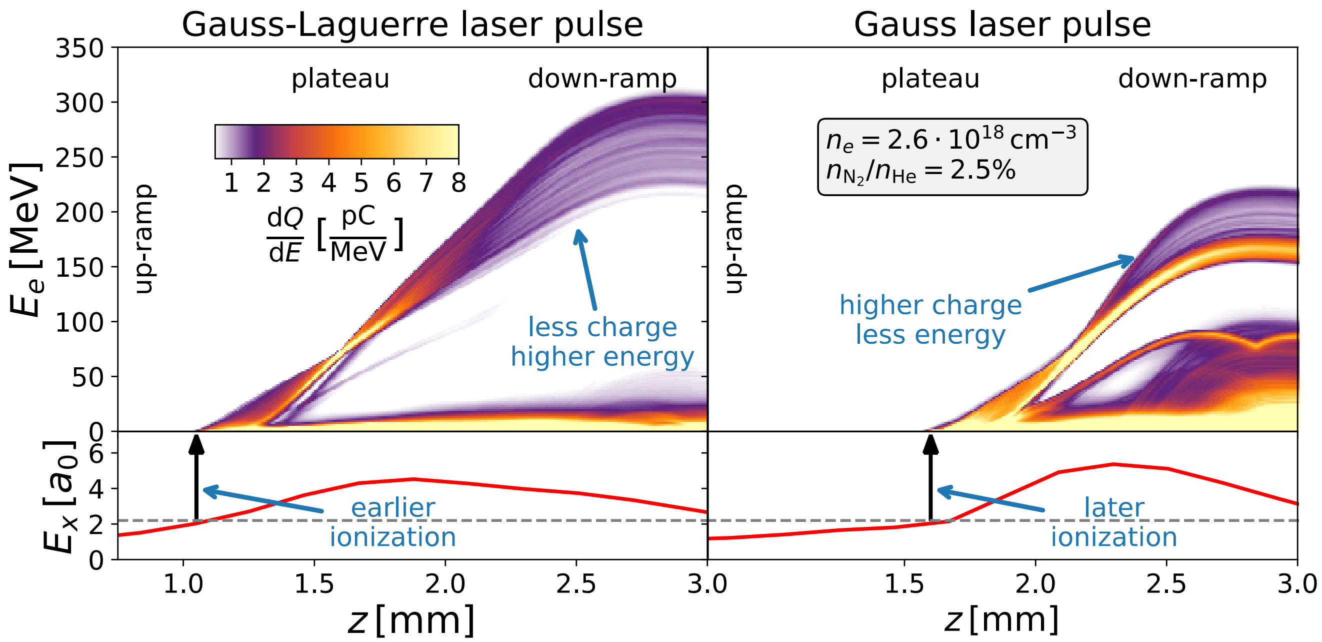
Laser modelling is key to improve LWFA stage predictions

1. Correct for real laser energy ← there was a degraded optical component causing energy decrease
2. Incorporate the measured intensity profile → It has a strong impact on electron injection
3. (There is still some uncertainty with respect to the laser focus position)

Comparison laser evolution Gauss / Gauss-Laguerre model

Resulting electron acceleration

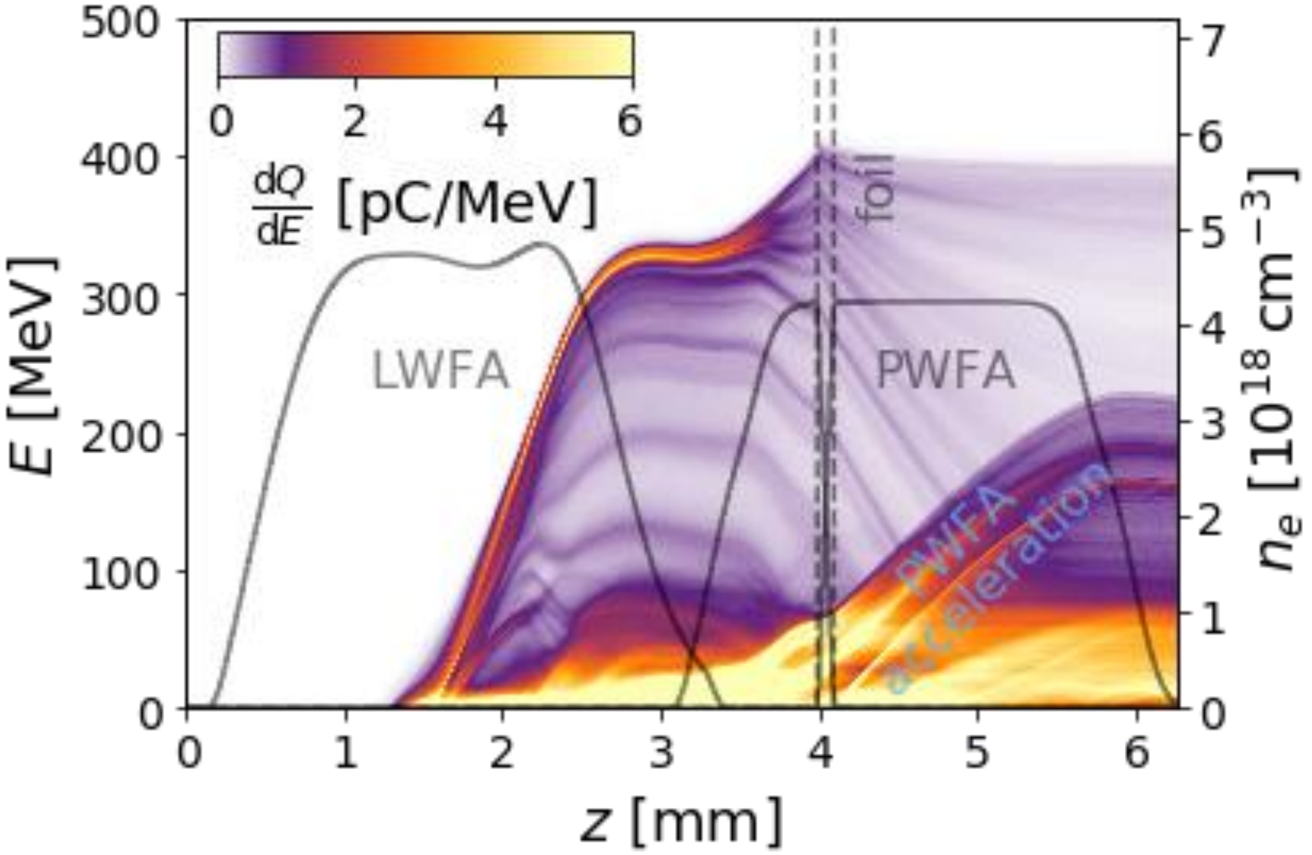




Now, where are we with respect to the total setup?

- reducing laser energy
- assuming previously measured laser modes
- adjusting the vacuum focus position

1.4-1.7 J laser energy

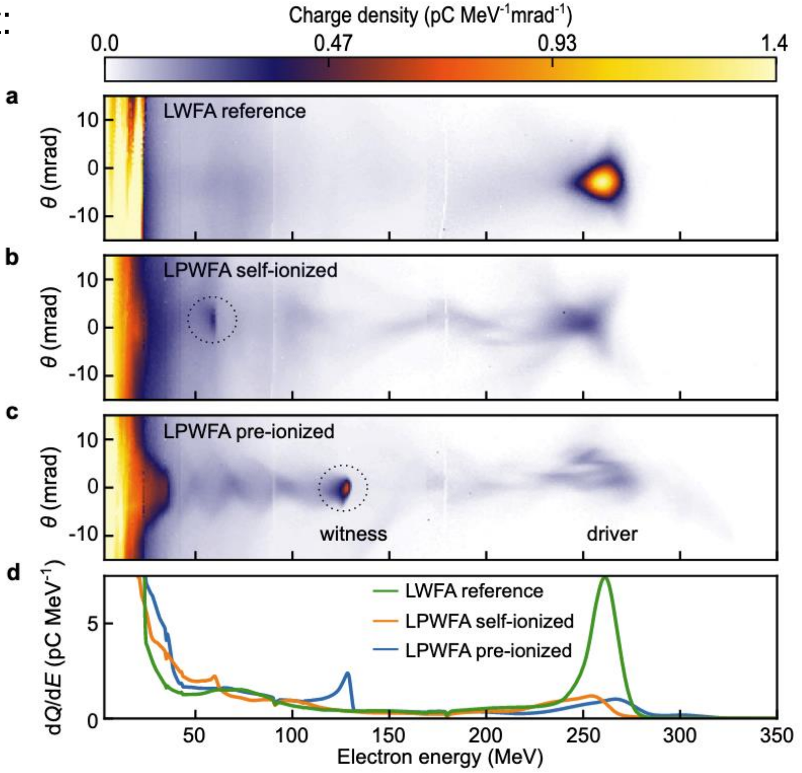


All in all we achieve very good agreement

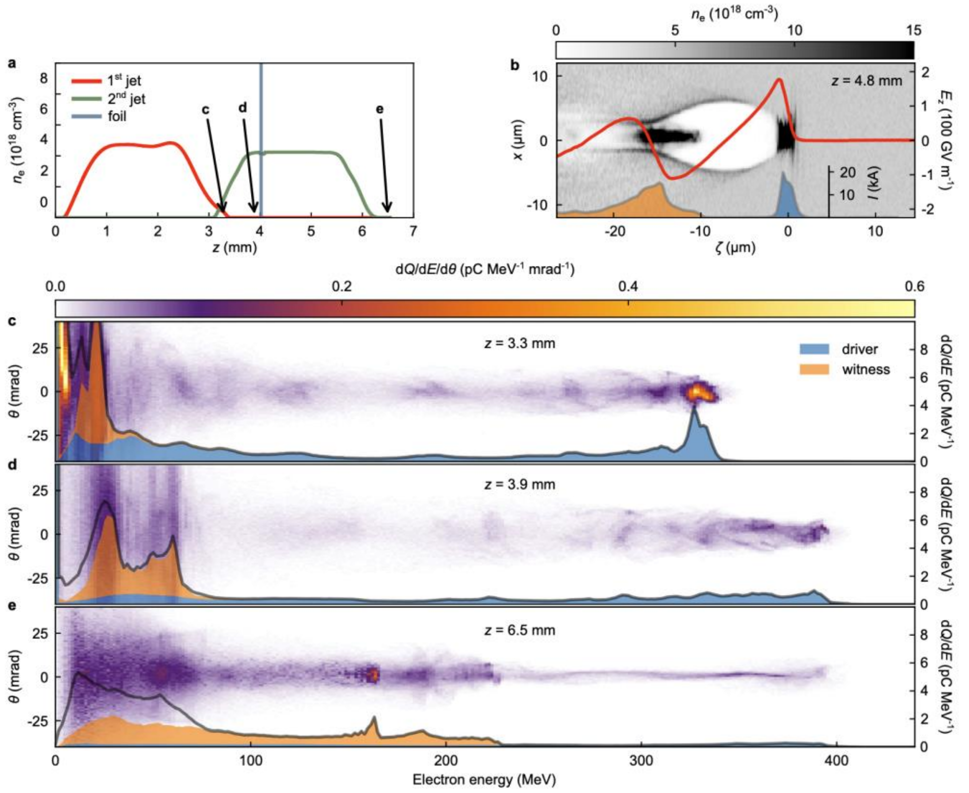
With modelling of **gas** and **laser** according to experiment measurements:

- Driver energy and energy spread reasonably close to experiment
- Driver degradation and witness acceleration as observed in experiment
- Witness peak energy in agreement with experiment

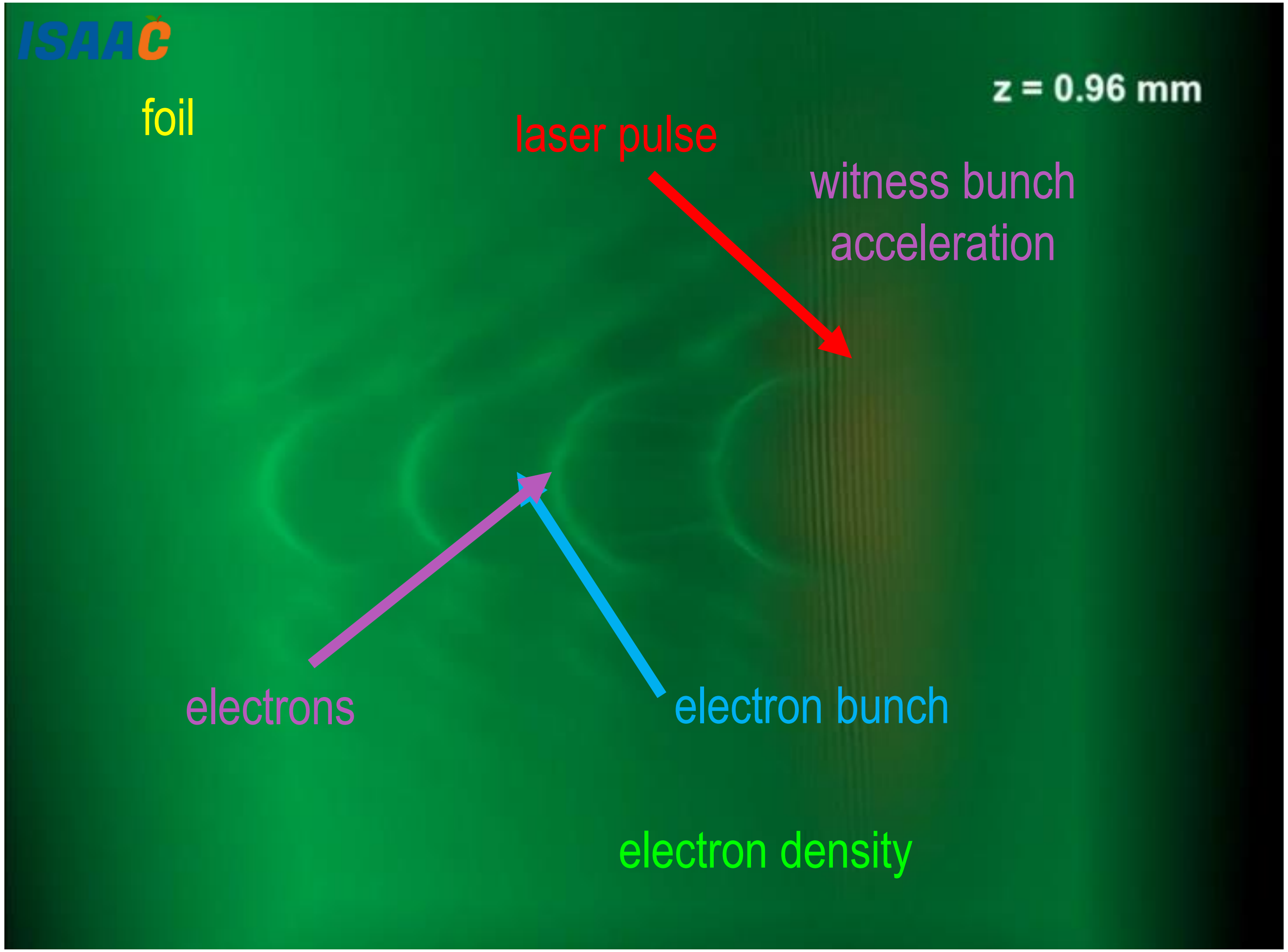
Experiment:



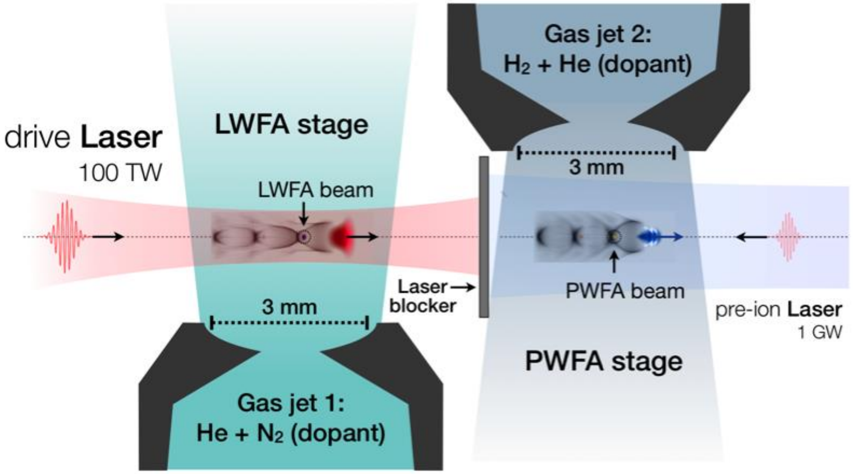
Simulation:



What we learn from the hybrid LPWFA simulation campaign



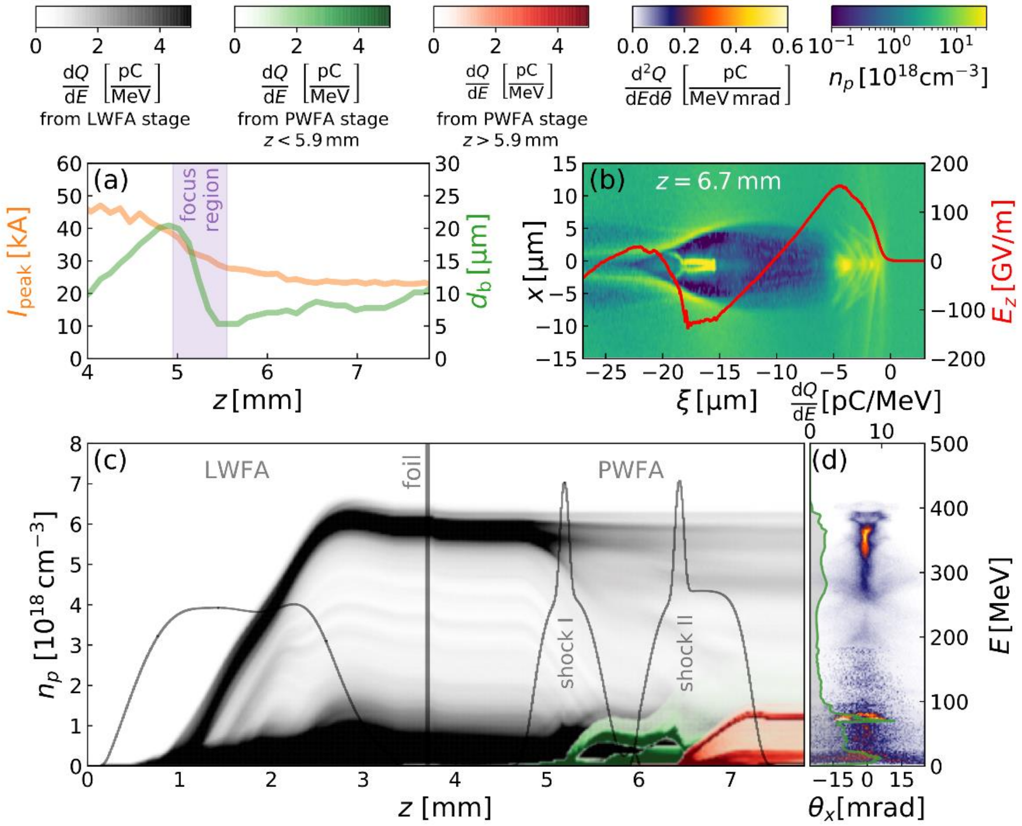
- Laser properties mainly determine LWFA performance
- Plasma lensing in the PWFA up-ramp is essential to maintain a strong driver
- Witness electrons originate in LWFA downramp



Simulation observations lead to improvements of LPWFA setup...

...which aim at controlling witness generation

1. Increase distance between LWFA and PWFA stage
2. Introduce shock in the PWFA stage with a wire



Simulations provided insight into complex dynamics:

- could explain complex beam self-focusing in-between stages
- double shock is (mostly) no issue – the first injection is decelerated
- density profile of shocks have significant impact on witness quality

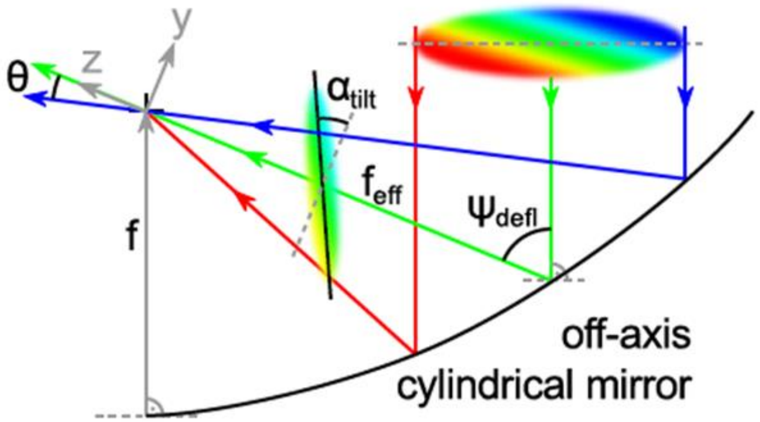
Gas-dynamic density downramp injection in a beam-driven plasma wakefield accelerator
J. Couperus Cabadağ et al., *PRR 3, L042005 (2021)*

And where we want to do better...

1. Laser dispersions are optimized in experiment to optimize LPWFA performance

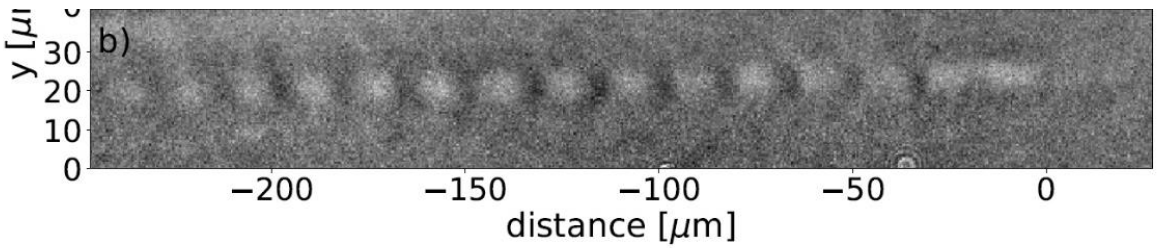
↑ previous modelling didn‘t take this into account

and spatio temporal couplings are ubiquitous



2. Shadowgraphy is an important experimental diagnostic that has the ability to compare and relate observations in experiments with observations in simulations

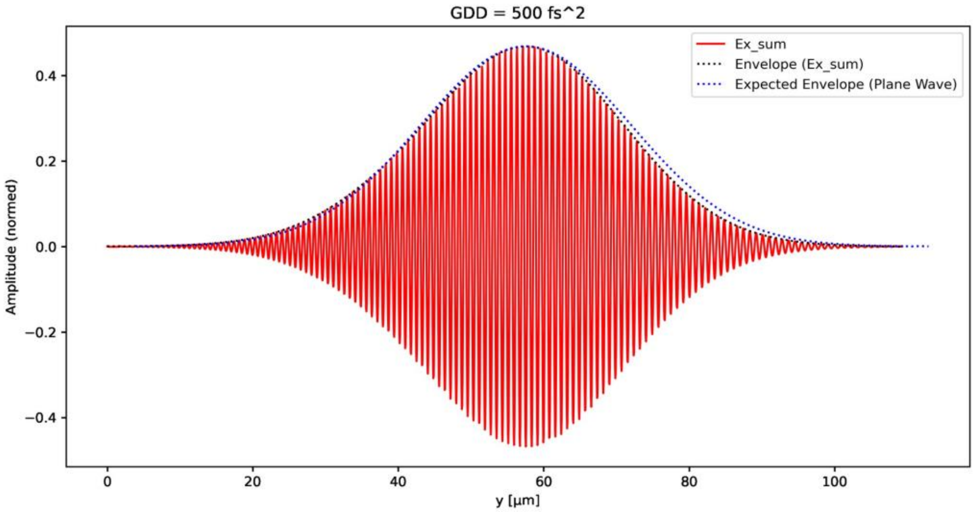
→ Shadowgraphy images do **not** directly show the electron density, we need to model this diagnostic

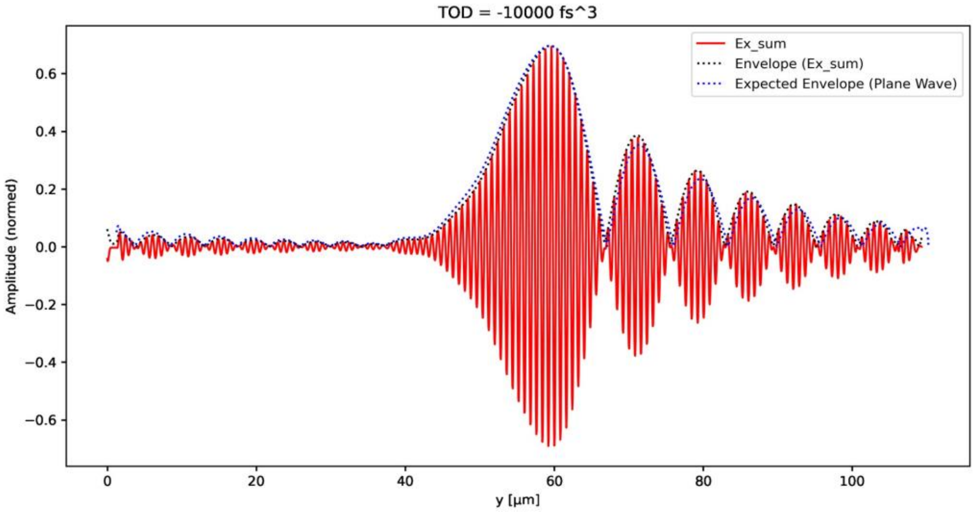


New laser models and initialization in PIConGPU

- further improved Gauss-Laguerre laser model in PIConGPU by adding complex phases
  ↪ more stable fitting to measurements

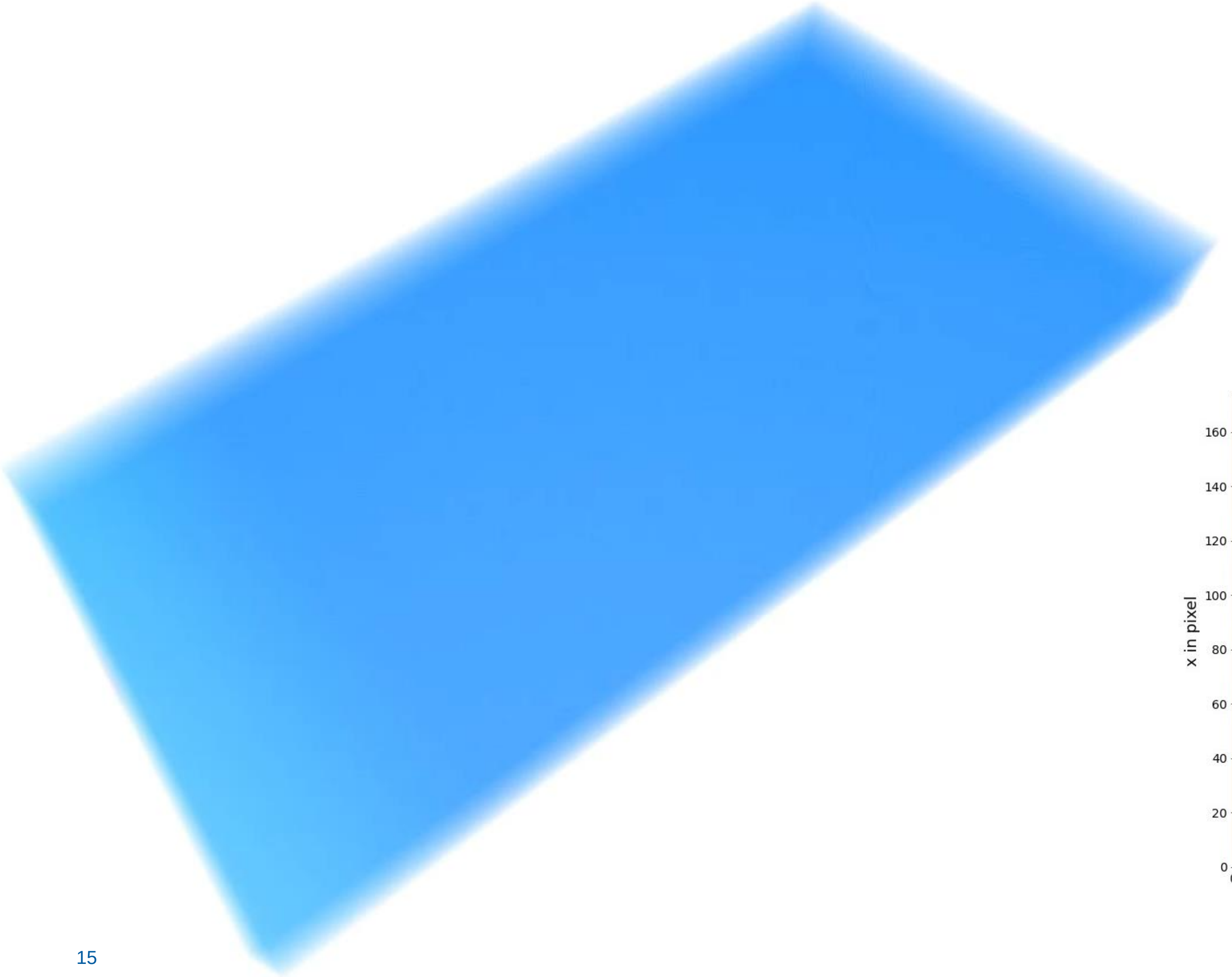
- spectral laser implementation
  ↪ allows to set GDD and TOD



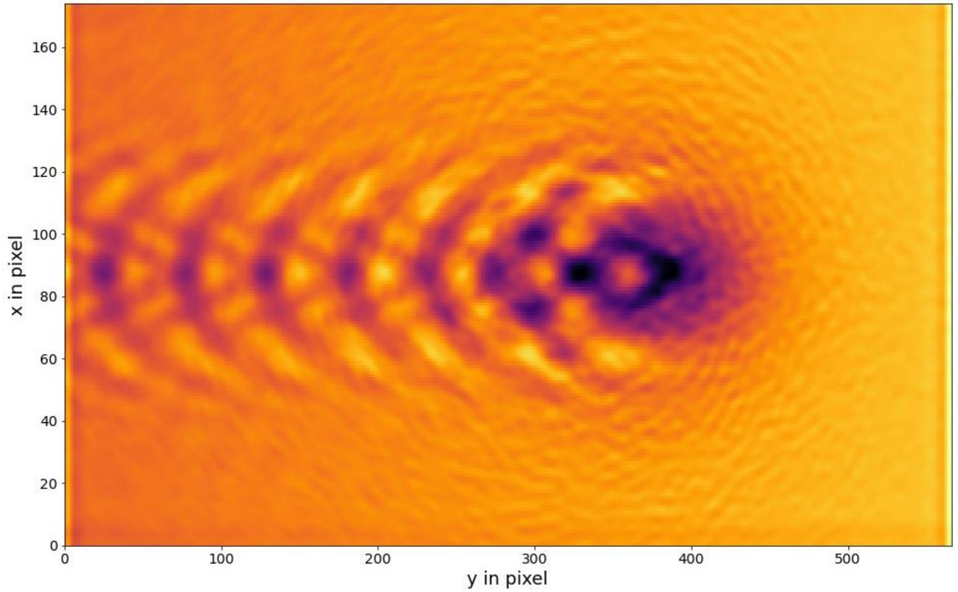


PWFA shadowgraphy

the better approach - in-situ shadowgram simulation



- probe laser is simulated directly with field solver
- propagation to camara modeled by plugin



PIConGPU

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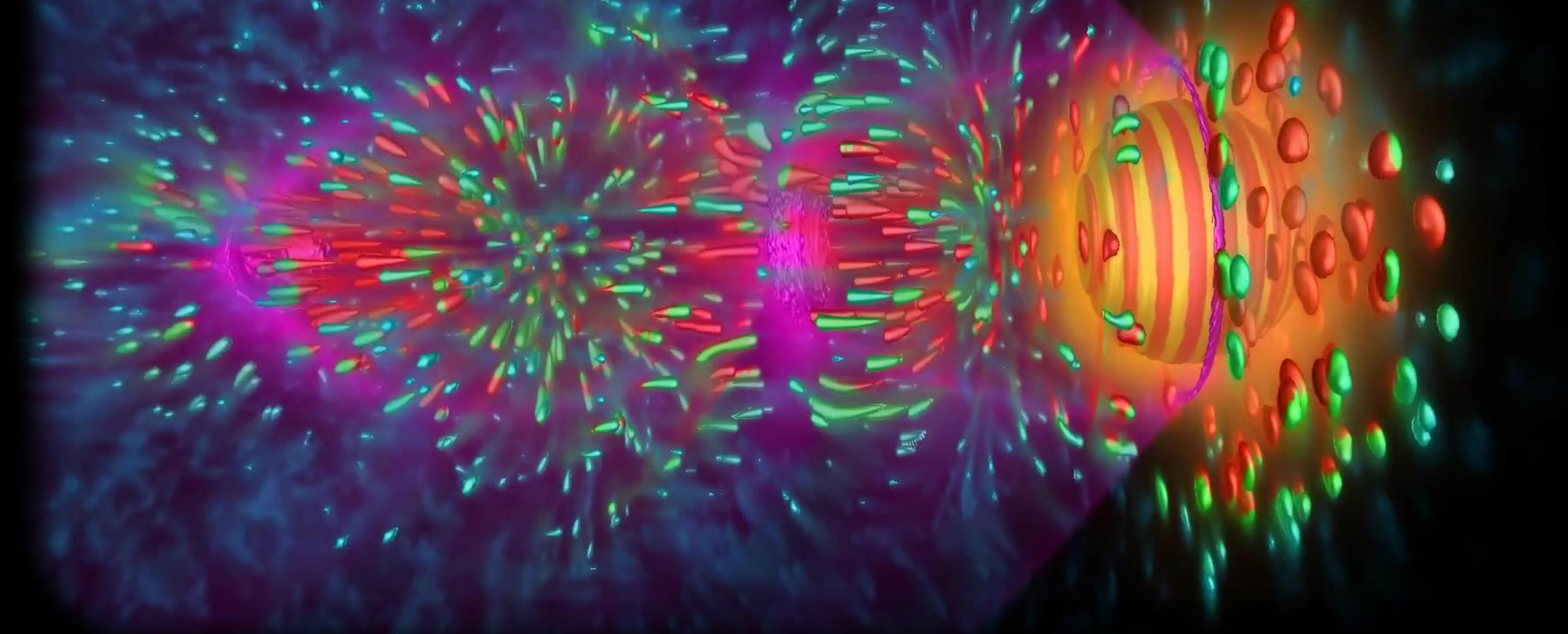
- **Good modelling fosters understanding of the observations we make in experiments**

- **We need to increase our ability to compare observations in experiment and theory against each other in order to benchmark our modelling efforts**



Courtesy: Felix Meyer, manuscript submitted.