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# Generating and testing flying focus laser pulses with Lasy for PIConGPU simulations

— A Bachelors Defense —

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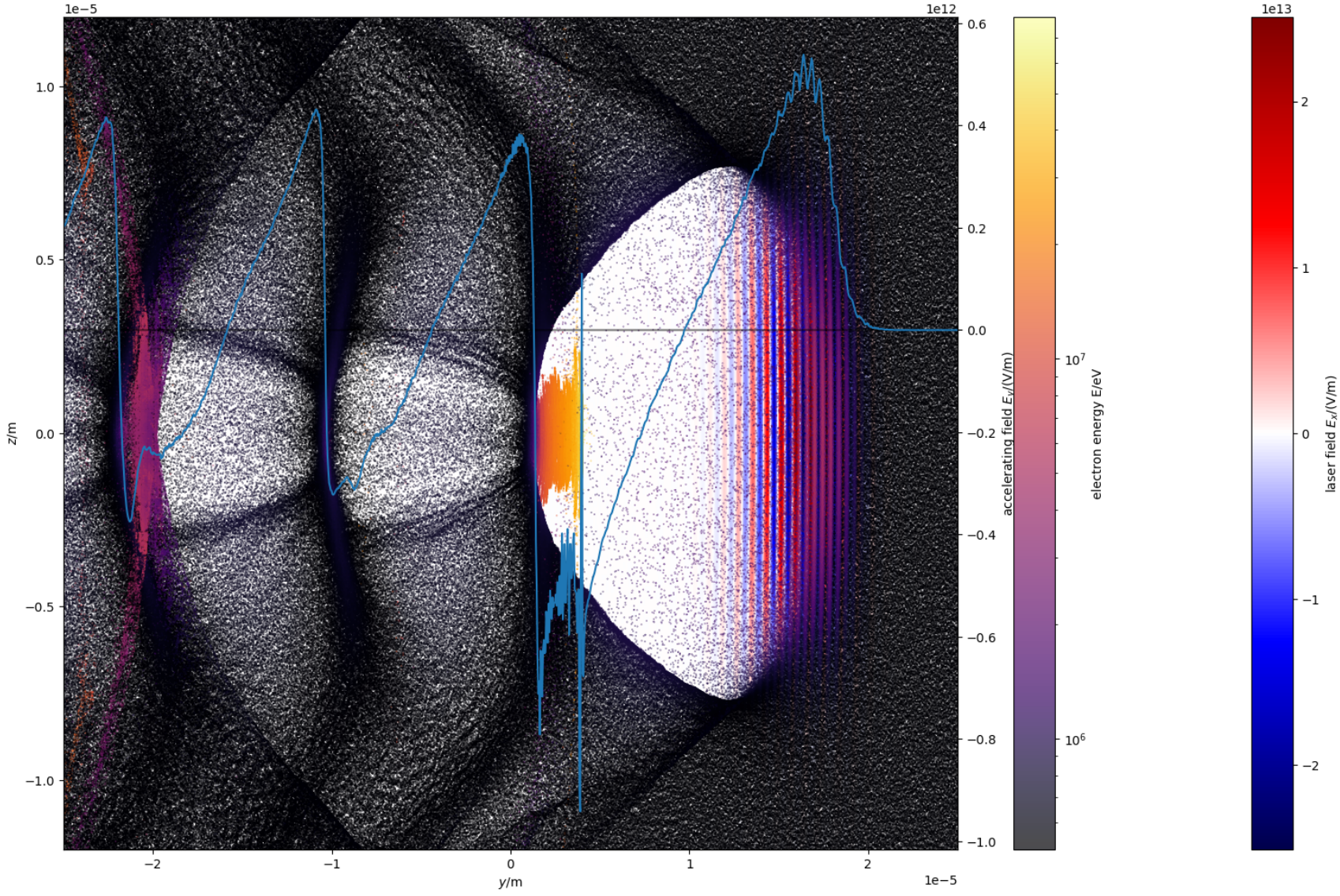
# Laser WakeField Acceleration (LWFA) [1]




Electric field and electrons in an LWFA simulation.



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# Flying focus lasers – solving the Problem of Dephasing

## 1. TWEAC [3]

- Traveling-Wave Electron ACcelerator
- Uses two laser pulses with tilted pulse fronts
- The tilt controls the velocity of the overlapping region

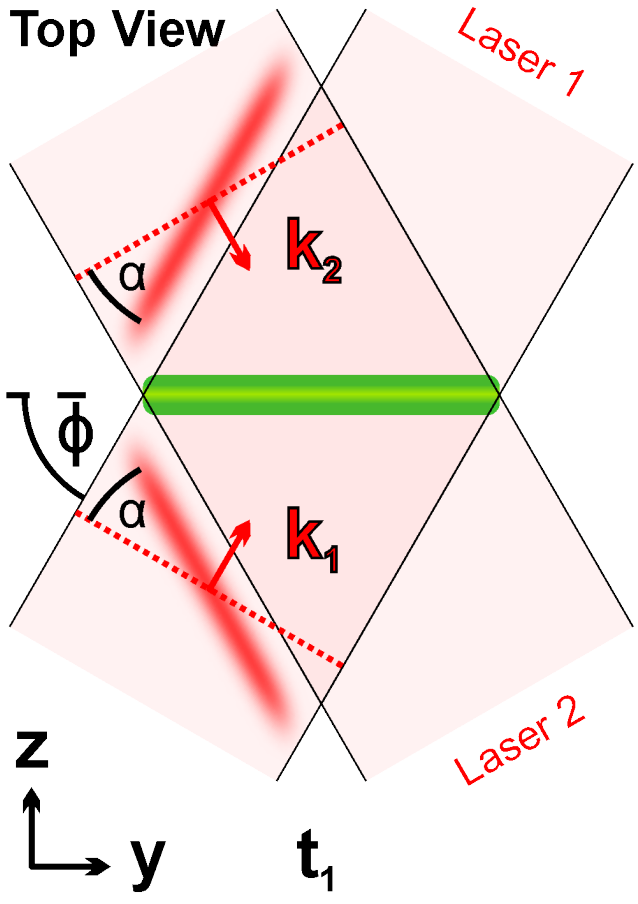


Image: TWEAC setup using two laser pulses. Image taken from Debus [2]

# Flying focus lasers – solving the Problem of Dephasing

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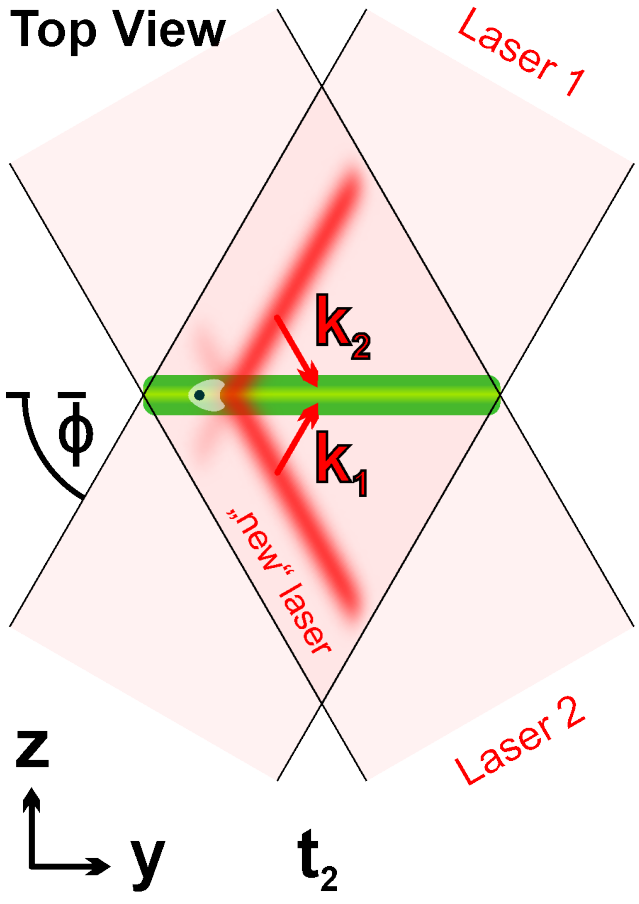


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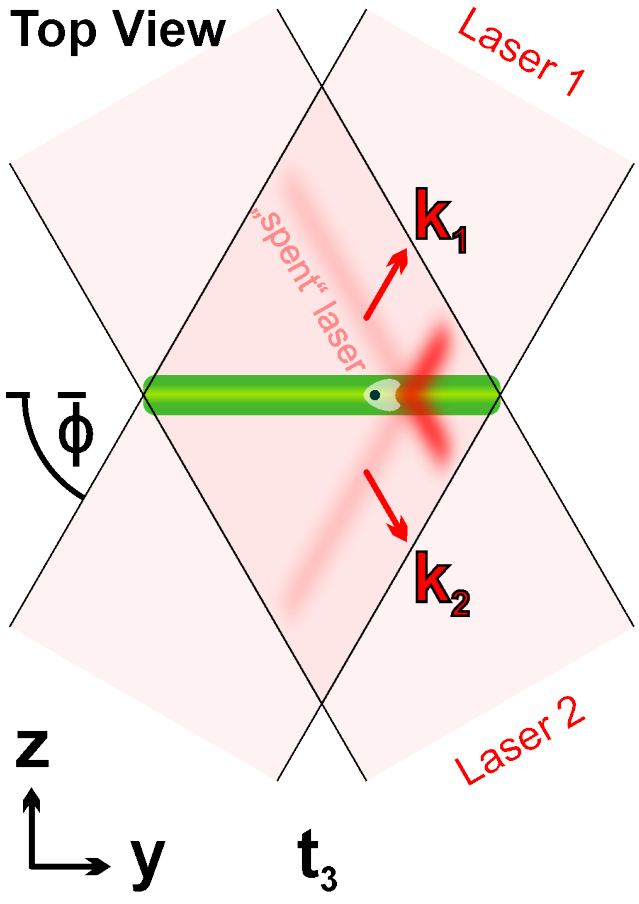


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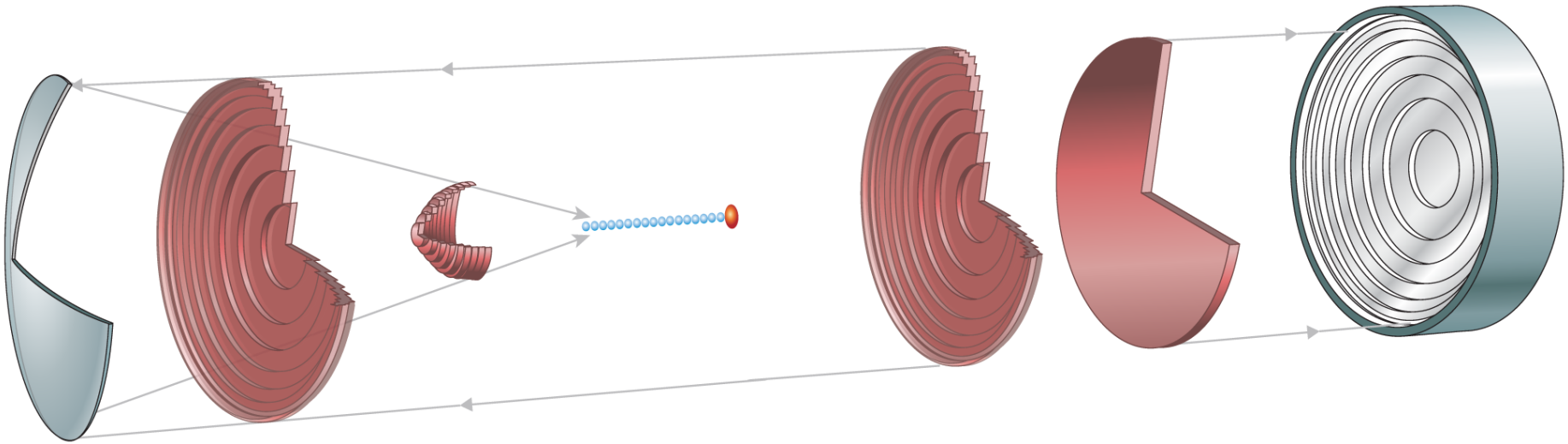
# Flying focus lasers – solving the Problem of Dephasing

## 2. Axiparabola laser [4]

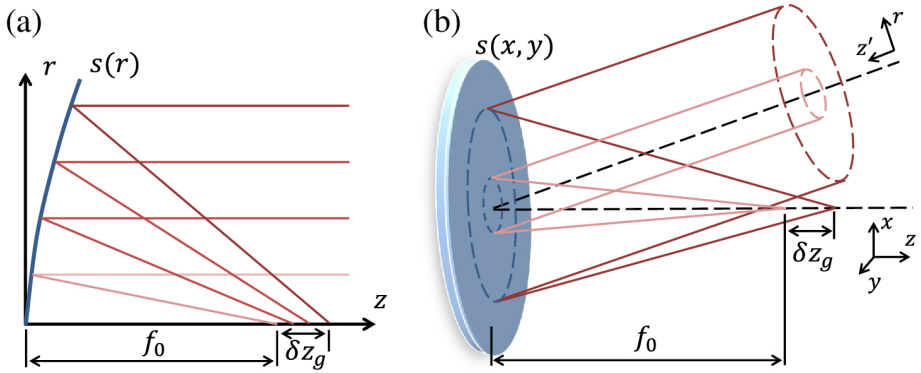


The flying focus setup. Two optical elements: The Axiparabola (left) and the Radial Group Delay echelon (RGD) (right). Image taken from Palastro et al [4].

# Flying focus lasers – solving the Problem of Dephasing

## 2. Axiparabola laser [4]

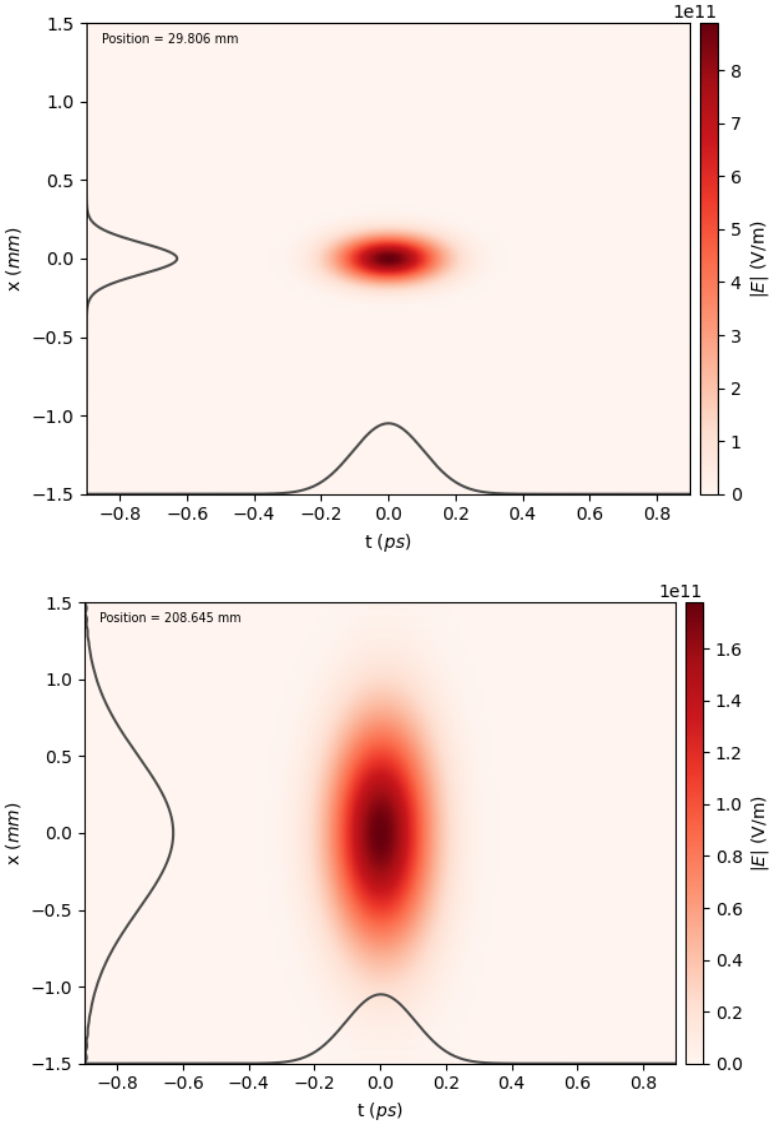
- Axiparabola [5]:
  - Near-parabolic mirror
  - Focuses light onto a line – the focus region
  - → Light at radius $r$ is focused at $f(r) = f_0 + \delta \left(\frac{r}{R}\right)^2$
- Radial Group Delay echelon (RGD) [6][4]:
  - Stepped concentric mirror rings
  - Shape follows some function $\tau_D(r)$
  - → controls the timing of the axiparabola focus




Axiparabola functionality. Image taken from Smartsev et al [5].

# Lasy [7]
## A python library

- A python library for simulating Laser pulses in a vacuum
- Uses complex envelope of the laser field
- Uses angular spectrum propagation
- Can use cylindrical coordinates for memory and CPU time efficiency
- Offers a range of optical elements

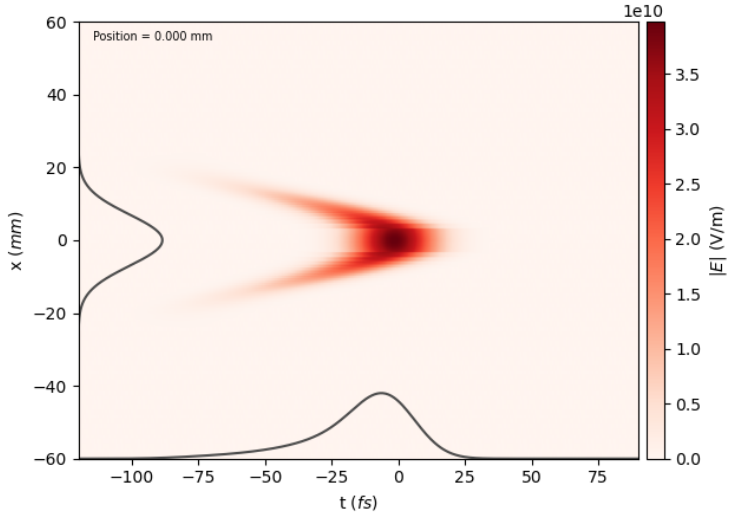


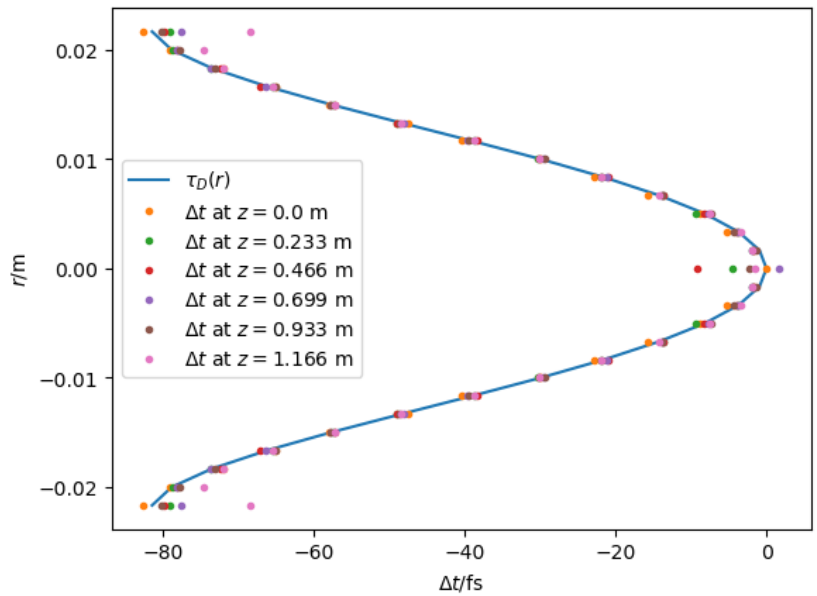

Images: Example of a Gaussian pulse being propagated by Lasy. Top: generated at the focus, Bottom: 6 $z_R$ after the focus.

# Implementing the flying focus

## 1. The Radial Group delay echelon (RGD)

- Implemented from scratch as Lasy optical element
- Following the description by Ambat et al [6]
- Shapes the pulse temporally without focusing or defocussing
- Can generate any radially symmetric shape of delay $\tau_D(r)$




Images: A Gaussian pulse after interacting with the RGD. Top: field envelope, Bottom: Test results. even after long distances the shape still holds.



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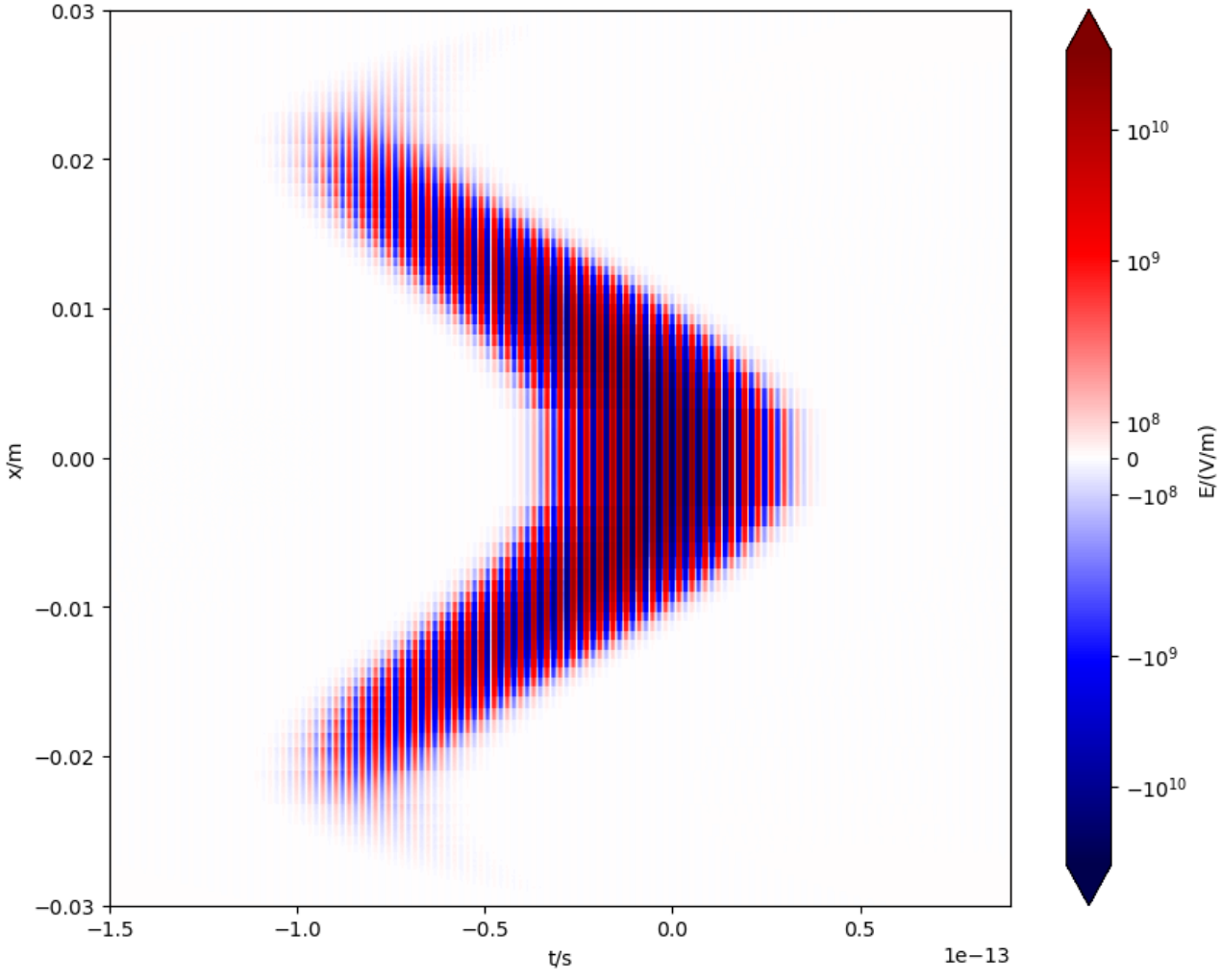
# Implementing the flying focus

## 1. The Radial Group delay echelon (RGD)

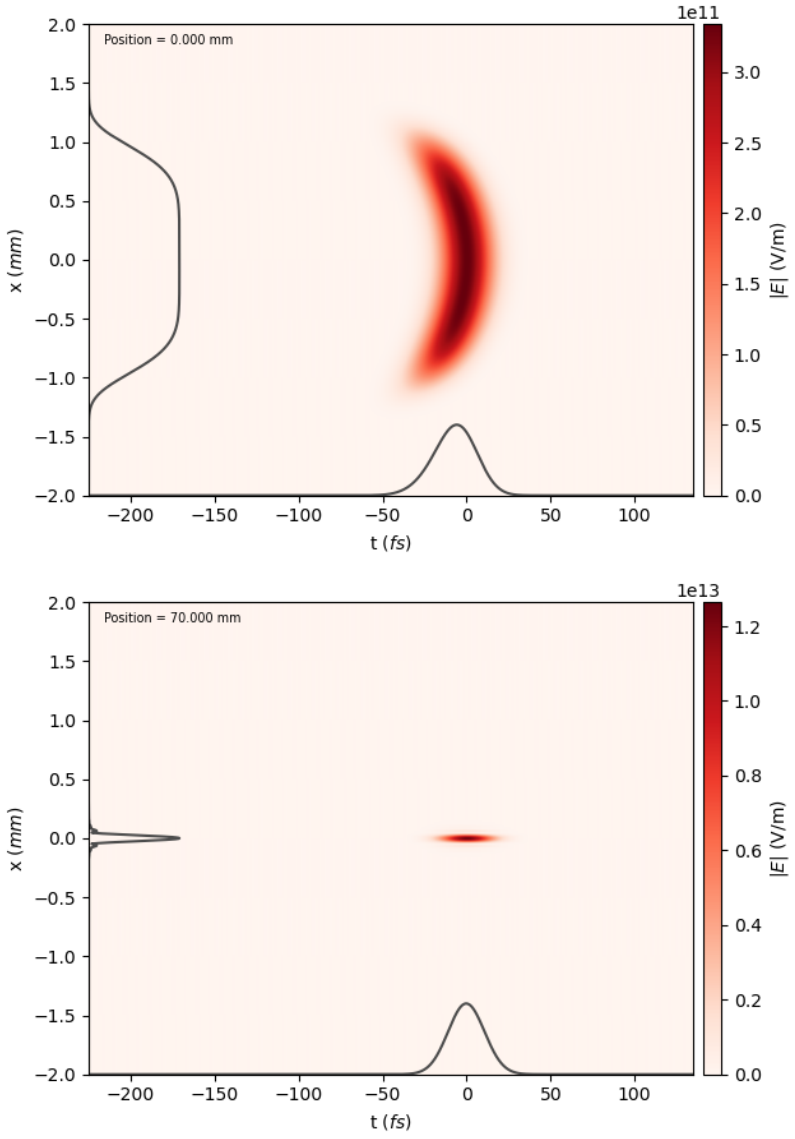



The electric field of the laser after interacting with the RGD.

# Implementing the flying focus

## 2. The Axiparabola

- Included in Lasy
- Following Smartsev et al [5]
- Focusing laser pulse in the focus region
- Also implemented an axiparabola following Ambat et al [6]
  - → Very small differences




Images: A super-Gaussian laser pulse after reflecting off the axiparabola. Top: in the near field, Bottom: in the far field at the beginning of the focus region.



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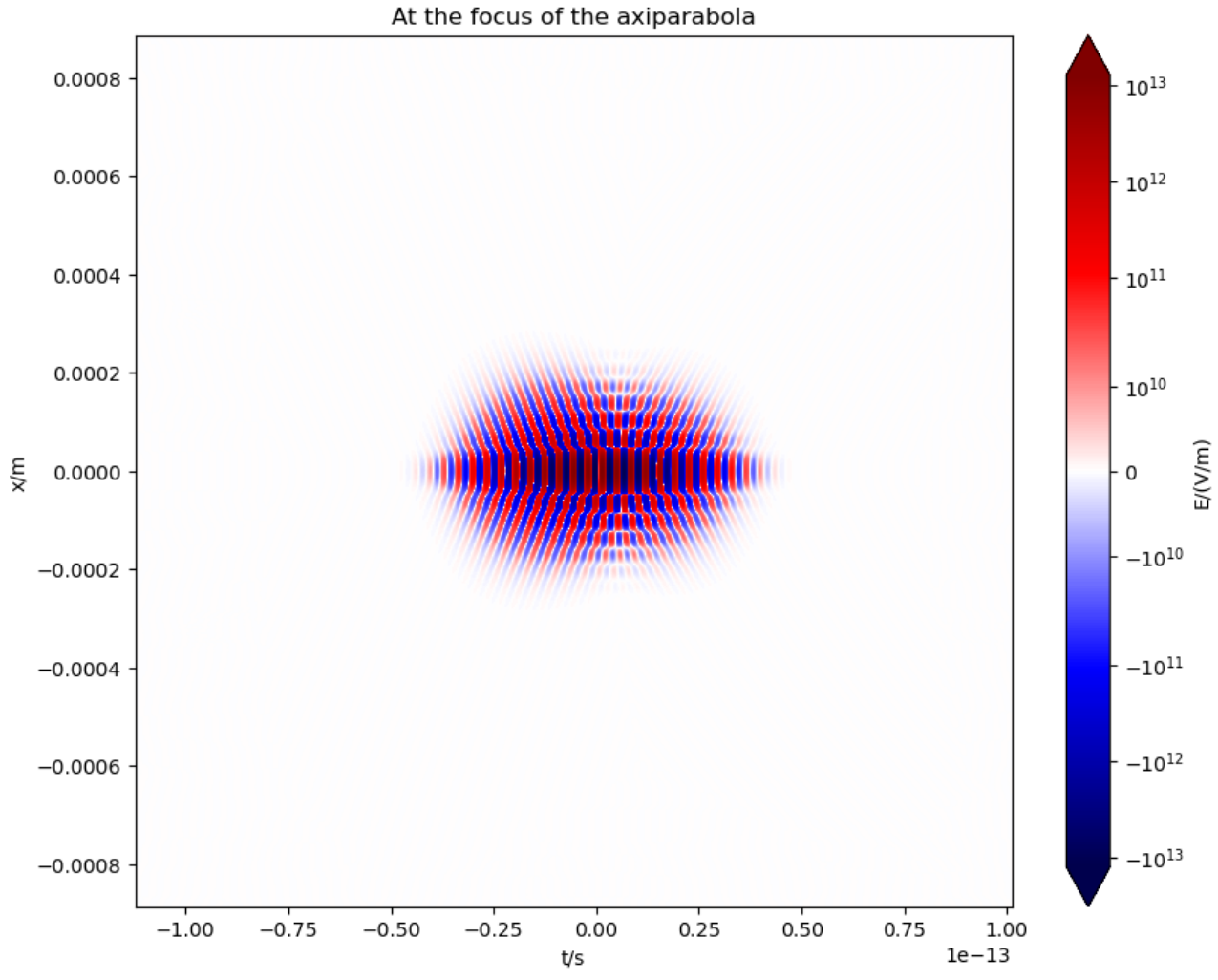
# Implementing the flying focus

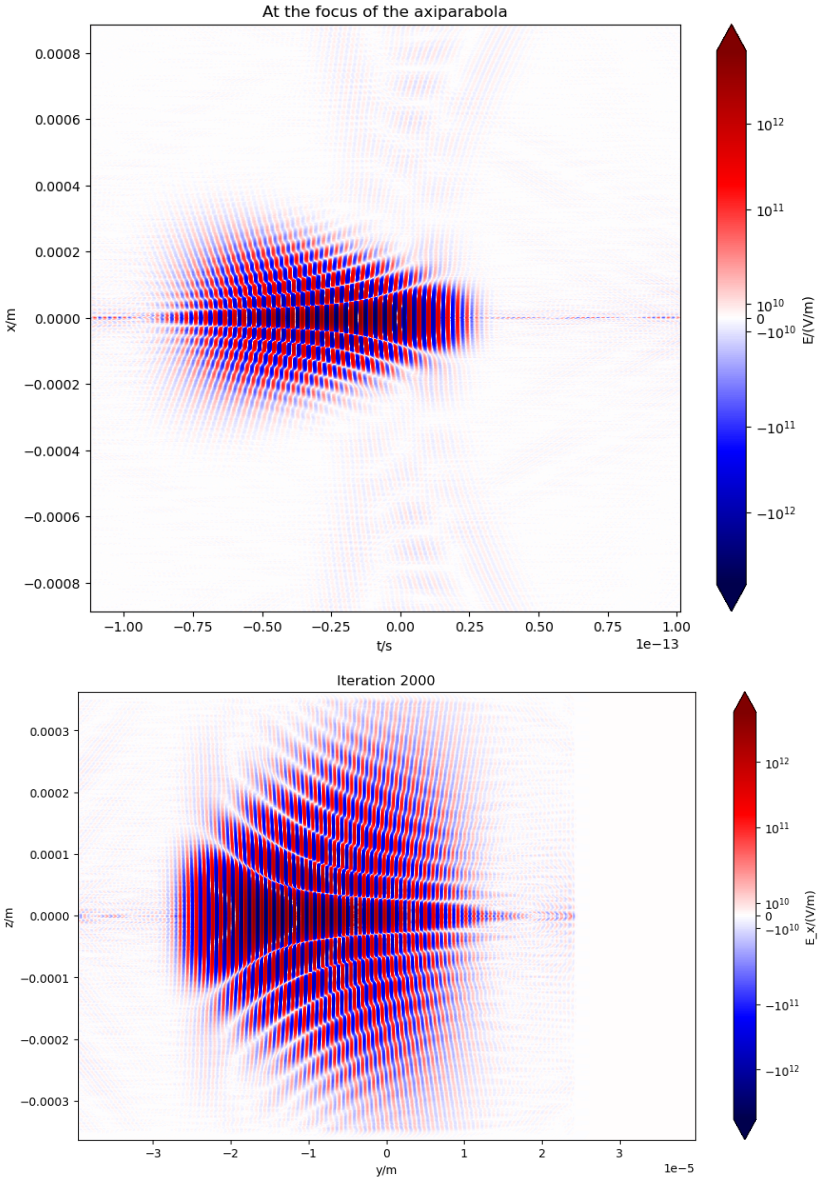
## 2. The Axiparabola




The electric field of the laser at the beginning of the focus region of the axiparabola.

# Importing to PIConGPU

- New module `full_field`
- Generates full electric field and saves it using `openPMD-api`
- incidentField method FromOpenPMDPulse [8] imports the field into PIConGPU

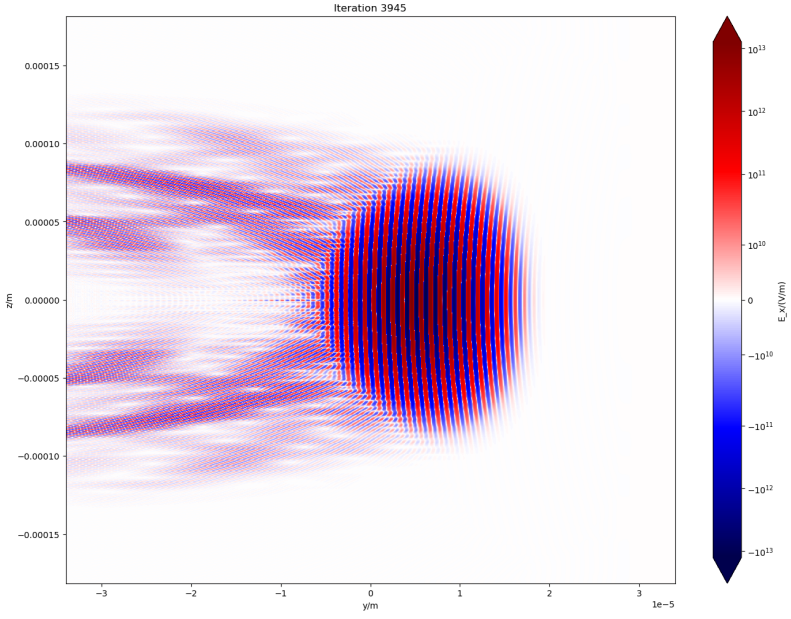


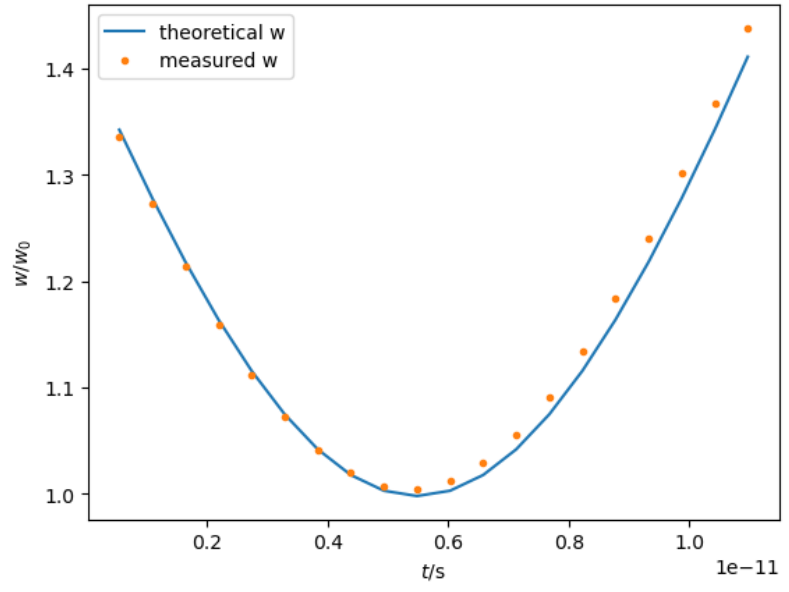

Images: Top: Electric field of the complete flying focus laser at the beginning of the focus region, Bottom: That same electric field entering the simulation window of a PIConGPU simulation.

# Testing the method

- Test with Gaussian laser pulse and parabolic mirror
- Some artifacts are visible
  - Problem of the incidentField method

  → See [9]
- Test successful




Images: Top: Electric field of the Gaussian laser pulse $z_R$ before the focus as imported into a PIConGPU simulation, Bottom: The beam waist $w$ of the pulse over time, compared to theory.



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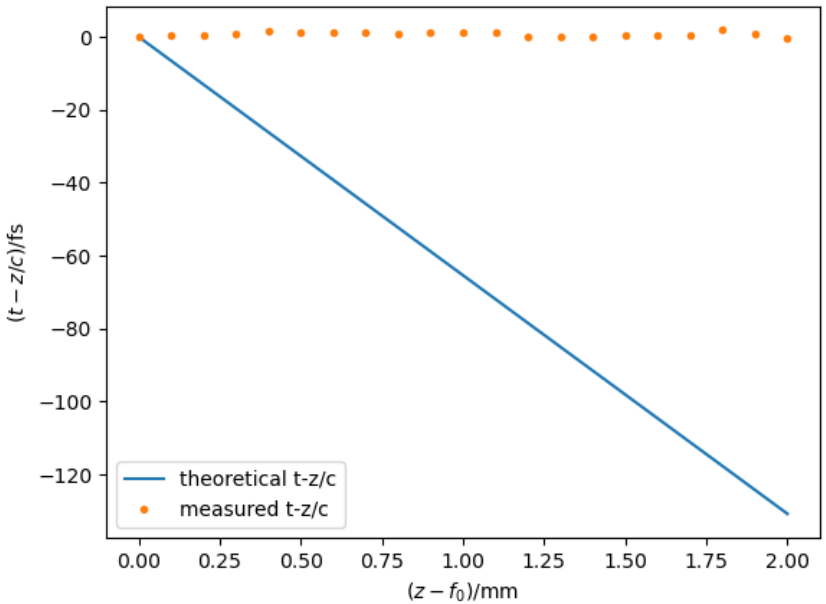
# Testing the flying focus laser

## First results

- It dont work
- I want it to though
- hmmm

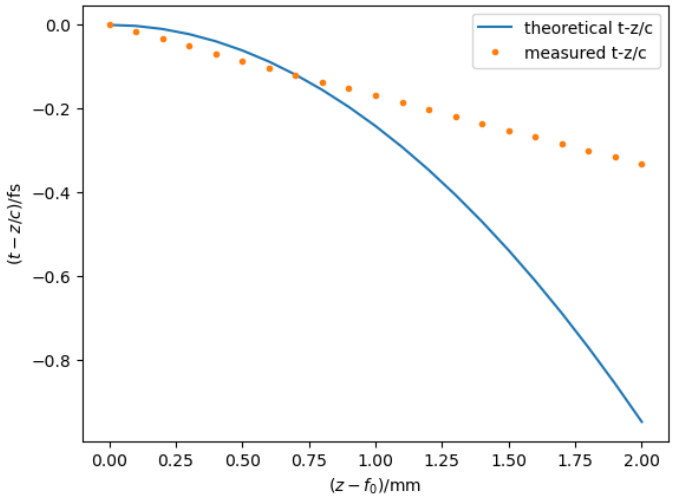
Images: Top: ?, Bottom: ?.

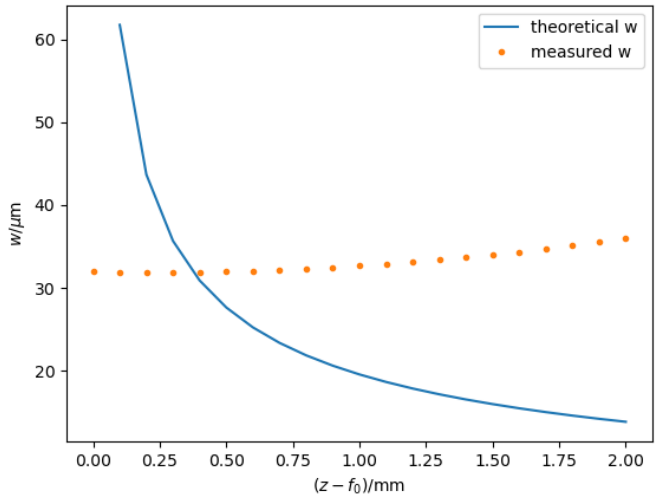


# Testing the flying focus laser

## Axiparabola only

- With only the axiparabola differences appear already
  - → Here must be the problem...
-




Images: Comparing measurements from a Lasy simulation with theoretical values using Ambat et al [6]. Top: Arrival time $t - z/c$, Bottom: Beam waist $w$.



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# Testing the flying focus laser

## More test?

Images:

# Conclusion

## Remaining Possible reasons for failure

- The Axiparabola
  - 
- The Propagation
  - 
- The Findings in the other papers
  - 

# Outlook

?

- Lasy lasers available in PIConGPU

→ ...

- LWFA with new laser setups possible

# References (I)


T Tajima and JM Dawson.
Laser electron-accelerator.
*Physical Review Letters*, 43(4), 1979.

Alexander Debus.
Traveling-wave electron accelerators.
AAC 2022 conference talk: `https://www.aac2022.org/`.

Alexander Debus, Richard Pausch, Axel Huebl, Klaus Steiniger, Rene Widera, Thomas E. Cowan, Ulrich Schramm, and Michael Bussmann.
Circumventing the dephasing and depletion limits of laser-wakefield acceleration.
*Physical Review X*, 9, 2019.

J. P. Palastro, J. L. Shaw, P. Franke, D. Ramsey, T. T. Simpson, and D. H. Froula.
Dephasingless laser wakefield acceleration.
*Phys. Rew. Letters*, 124, 2020.

# References (II)


Slava Smartsev, Clement Caizergues, Kosta Oubrerie, Julien Gautier, Jean-Philippe Goddet, Amar Tafzi, Kim Ta Phuoc, Victor Malka, and Cedric Thaury.
Axiparabola: a long-focal-depth, high-resolution mirror for broadband high-intensity lasers.
*Optics Letters*, 44, 2019.

M. V. Ambat, J. L. Shaw, J. J. Pigeon, K. G. Miller, T. T. Simpson, D. H. Froula, and J. P. Palastro.
Programmable-trajectory ultrafast flying focus pulses.
*Optics Express*, 31(19), 2023.

Lasy 0.6.2 documentation.
`https://lasydoc.readthedocs.io/en/latest`.
Accessed october 2025.

Fabia Dietrich.
Implementation and validation of a method for using experimentally measured laser profiles in laser-plasma simulations with picongpu.
Master's thesis, HZDR, TU Dresden, 2024.

# References (III)

Klaus Steiniger.
Issue 5269 todo in laser refactoring.
https://github.com/ComputationalRadiationPhysics/picongpu/issues/5269.
Accessed october 2025.