

Generating and testing flying focus laser pulses with Lasy for PICGPU simulations

—A Bachelors Defense—

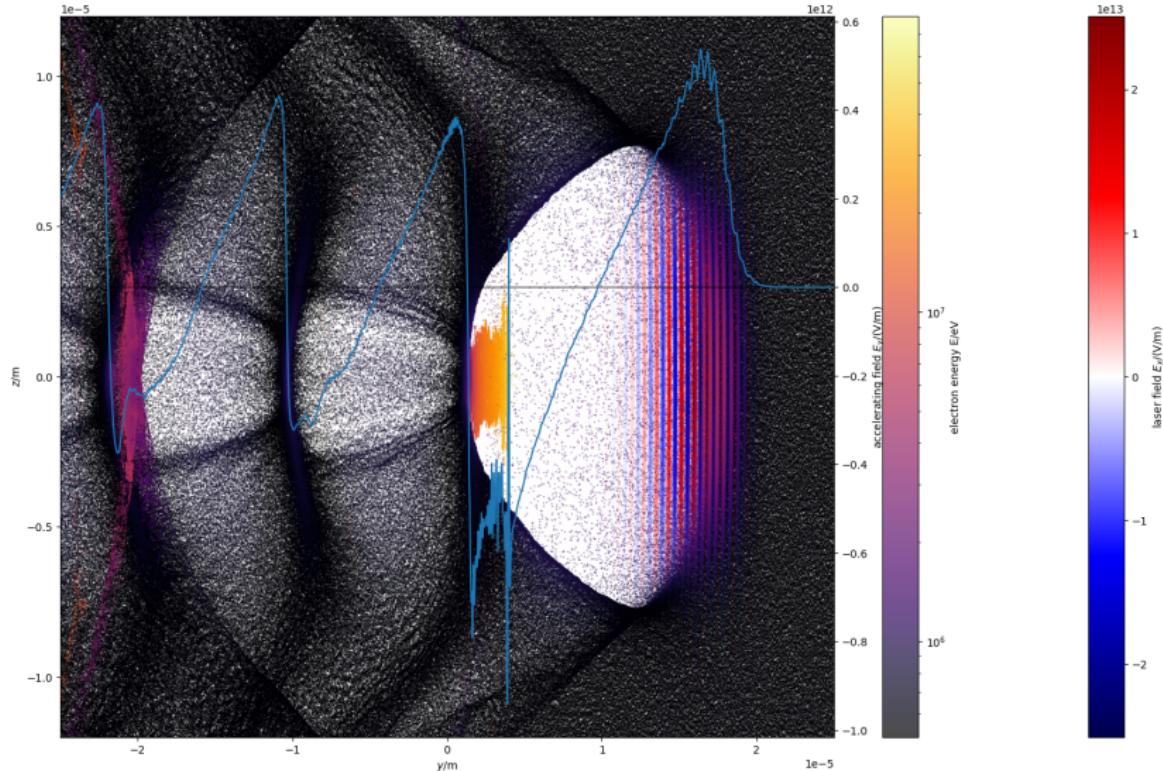
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- 1 Dephasingless Laser WakeField Acceleration (DLWFA)
- 2 Flying focus lasers in Lasy and PICoGPU
- 3 Testing the flying focus lasers
- 4 Conclusion and Outlook
- 5 References

Laser WakeField Acceleration (LWFA) [1]



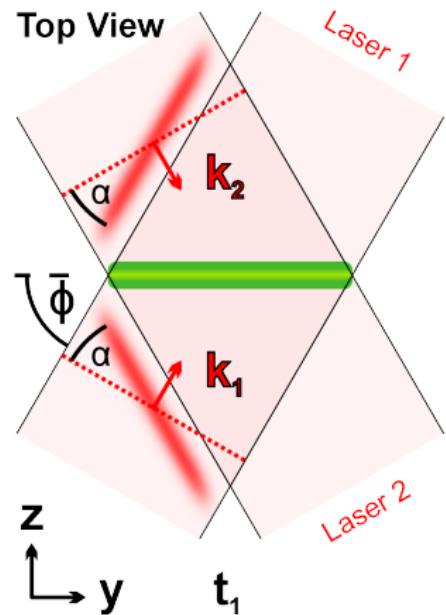
Electric field and electrons in an LWFA simulation.

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]

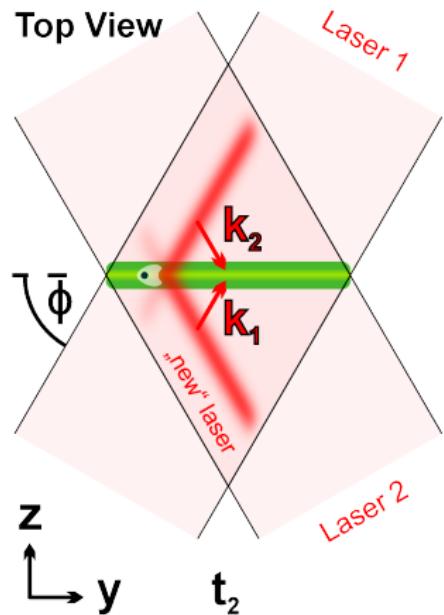


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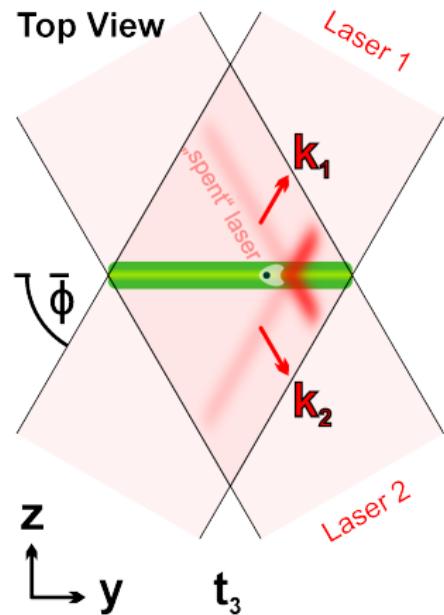


Flying focus lasers – solving the Problem of Dephasing

1. TWEAC [3]

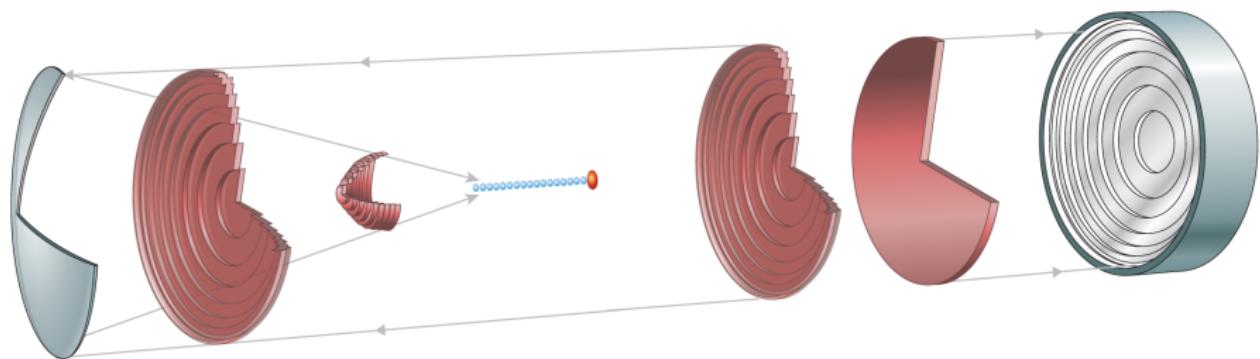
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Flying focus lasers – solving the Problem of Dephasing

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

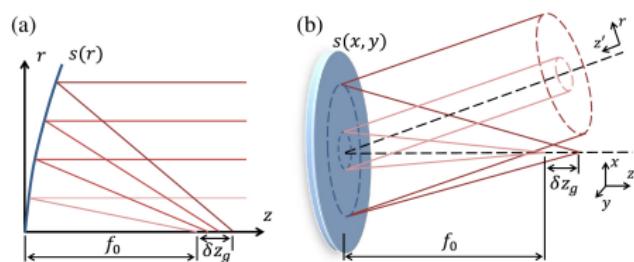
2. Axiparabola laser [4]

■ 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



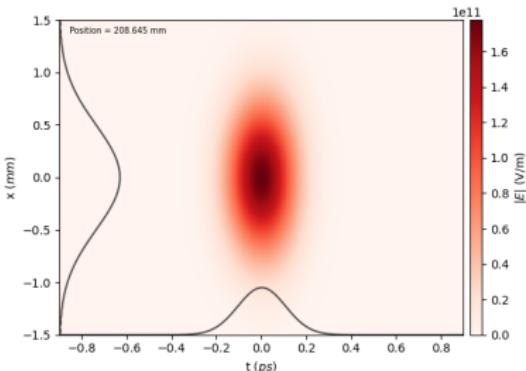
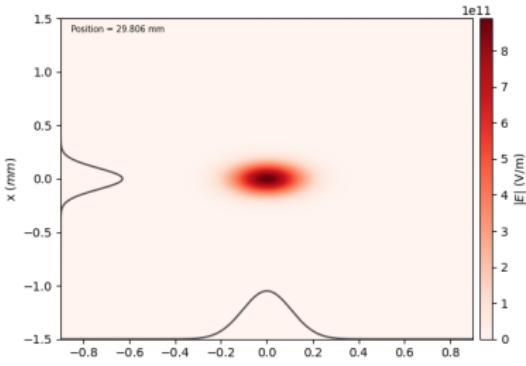
Axiparabola functionality. Image taken from Smartsev et al [5].

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

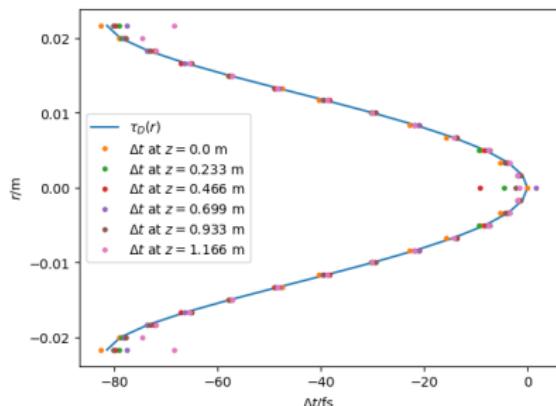
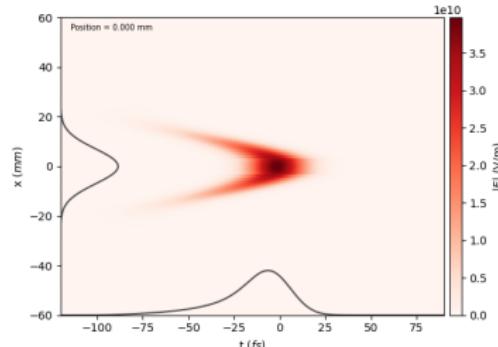
Images: Example of a Gaussian pulse being propagated by Lasy. Top: generated at the focus, Bottom: 6 z_R after the focus.



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 $\tau_D(r)$

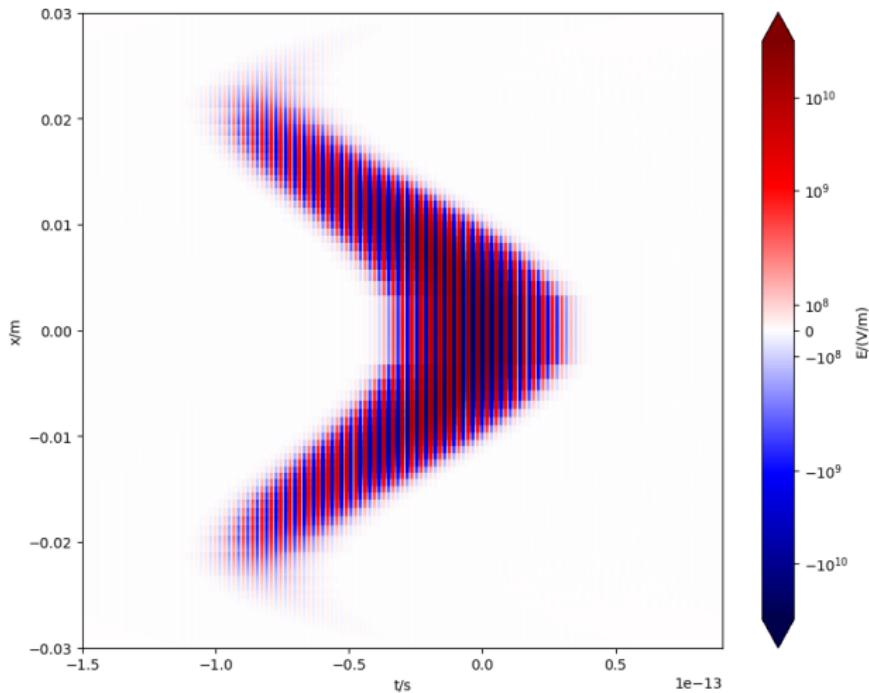


Images: A Gaussian pulse after interacting with the RGD.

Top: field envelope, Bottom: Test results. even after long distances the shape still holds.

Implementing the flying focus

1. The Radial Group delay echelon (RGD)



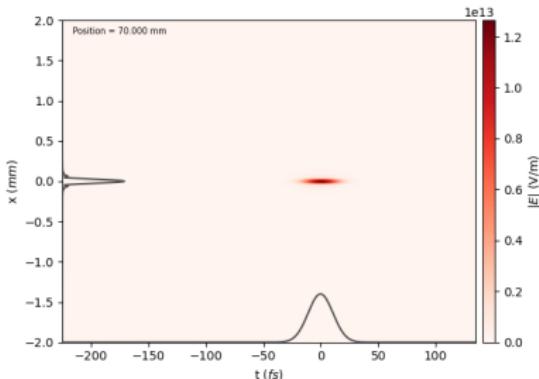
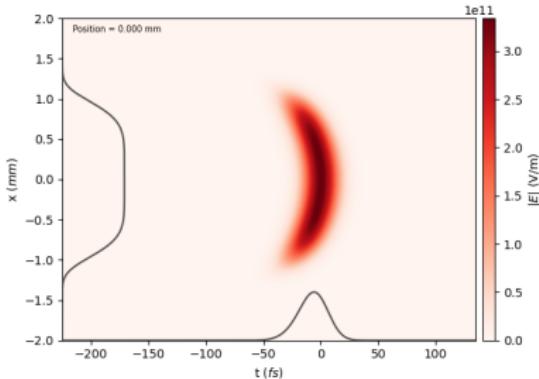
The electric field of the laser after interacting with the RGD.

Implementing the flying focus

2. The Axiparabola

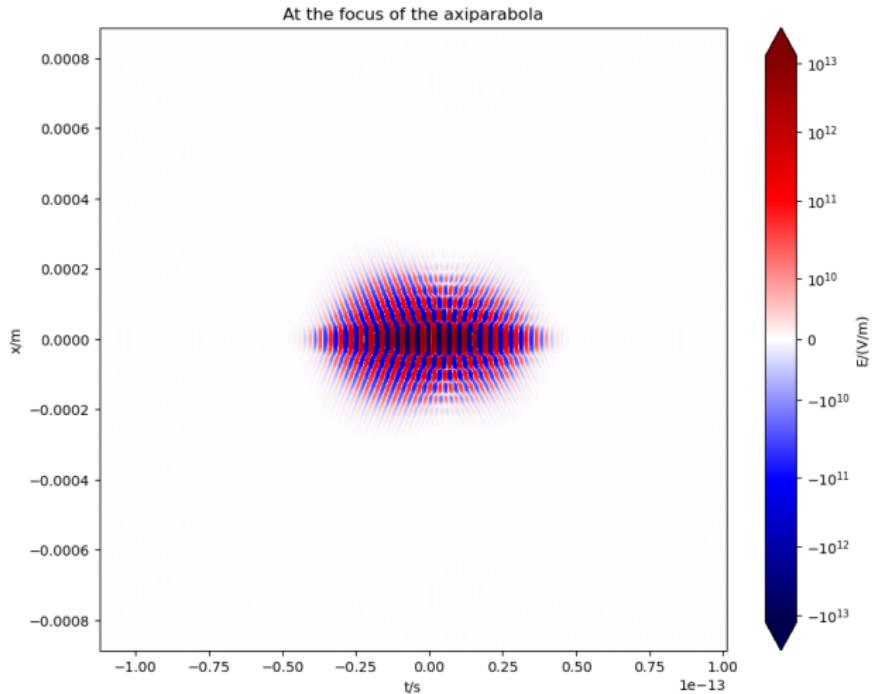
- Included in Lasy
- Following Smartsev et al [5]
- Focusing laser pulse in the focus region
- Also implemented an axiparabola following Ambat et al [6]
 - Very small differences

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.



Implementing the flying focus

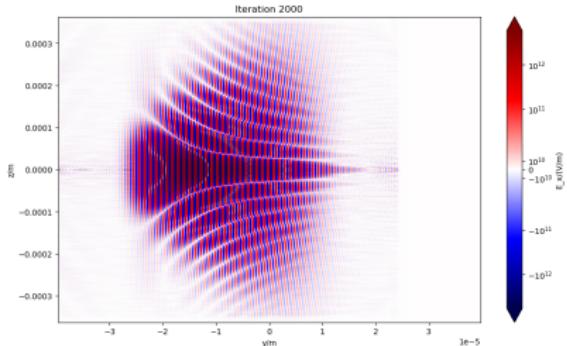
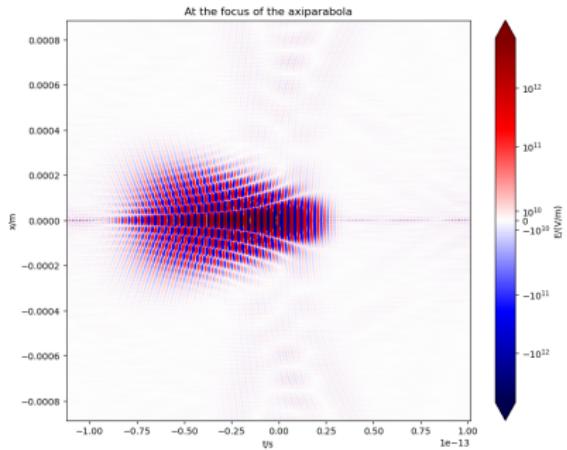
2. The Axiparabola



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

Importing to PIConGPU

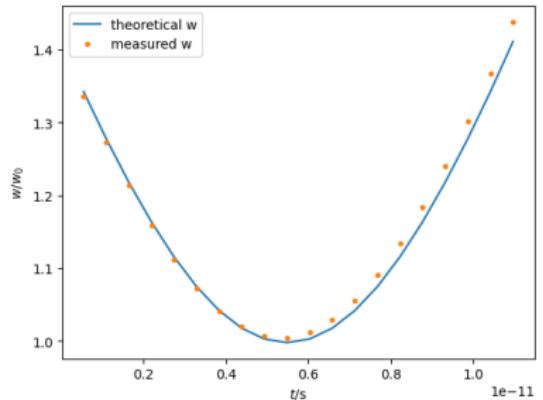
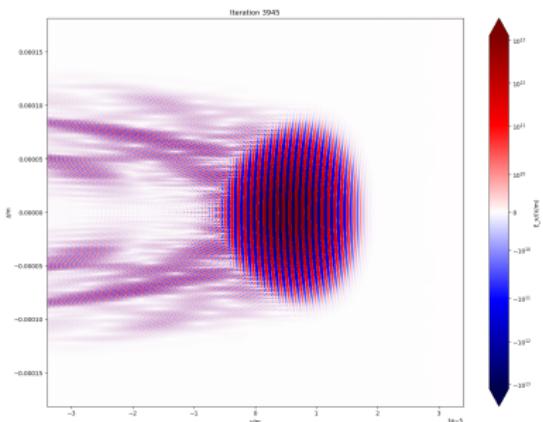
- New module `full_field`
- Generates full electric field and saves it using openPMD-api
- `incidentField` method
FromOpenPMDPulse [8] imports the field into PIConGPU



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



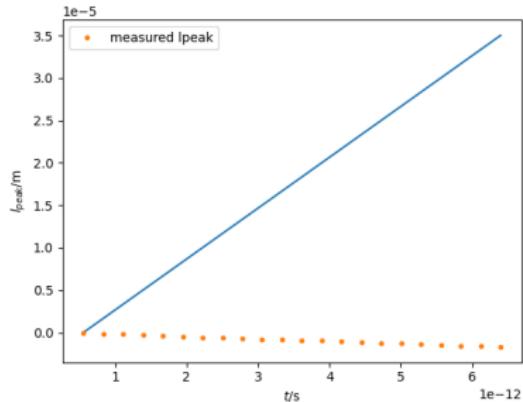
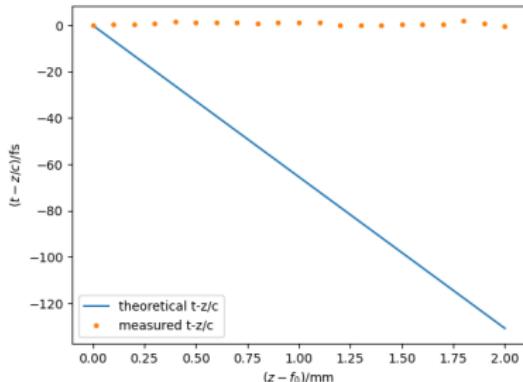
Images: Top: Electric field of the Gaussian laser pulse z_R before the focus as imported into a PIConGPU simulation,
Bottom: The beam waist w of the pulse over time,
compared to theory.

Testing the flying focus laser

First results

- Simulations in Lasy and PICoGPU
 - Input file for PICoGPU saved at the beginning of the focus region
 - Result: The flying focus effect cannot be seen
- Test failed

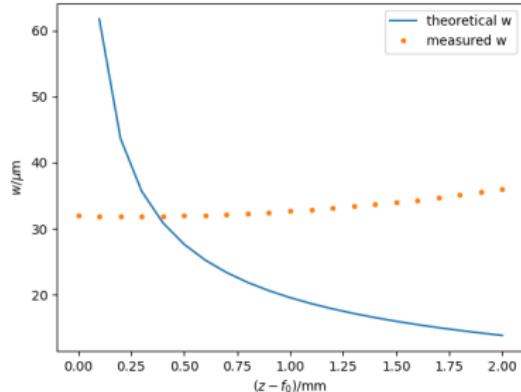
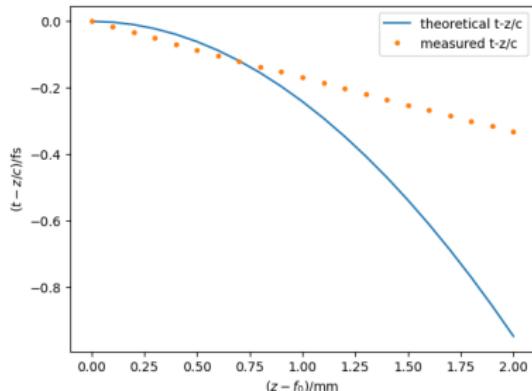
Images: Comparing measurements from the simulations to the expected evolution. Top: From a Lasy simulation:
 $t - z/c$, Bottom: From a PICoGPU simulation: $z - t \cdot c$.



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 .

Conclusion

Remaining Possible reasons for failure

- The Axiparabola
 - The shape could still be wrong
- The Propagation
 - Possibly the Lasy propagation gives incorrect/incomplete results
- The Findings in the other papers
 - Maybe the Axiparabola does not work at all
 - Maybe it works in a different manner
- Maybe something else...

Outlook

- Easy lasers available in PICoGPU
- LWFA with new laser setups possible
- Some problems still need resolving

(*) There's more to explore here.

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Klaus Steiniger.

Issue 5269 todo in laser refactoring.

[https://github.com/ComputationalRadiationPhysics/picongpu/
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Accessed october 2025.