Laboratoire Interactions, Dynamiques et Lasers
EMR9000 CEA, CNRS, Université Paris-Saclay

A novel laser-driven electron scheme based on a plasma-mirror injector

Thomas Clark

15/11/2023

PHI
PHYSICS AT HIGH INTENSITY

O. Gobert

T. Ceccotti

A. Panchal

A. Ammar

Experiments

K. Oubrerie

P. Forestier-Colleoni

S. Dobosz Dufrénoy

I. Kara-Mostefa

Theory/simulations

H. Vincenti
(head of numerical division)

P. Martin

L. Fedeli

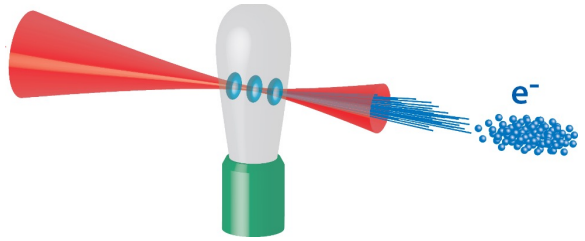
T. Clark

P. Bartoli

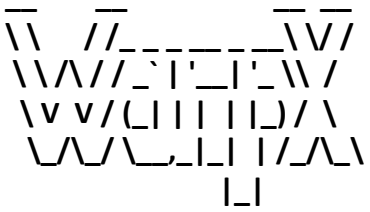
Laboratoire d'optique Appliquée – UPX team
Experimental team (Adrien):

A. Leblanc

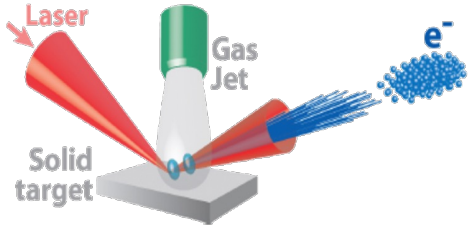
Outline



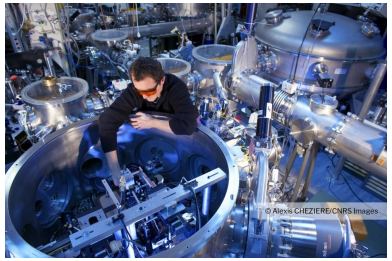
The idea of the Hybrid Target



WarpX : an exascale PIC code

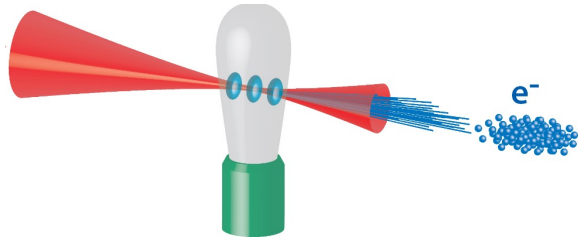


Numerical study



Experimental validation

Outline



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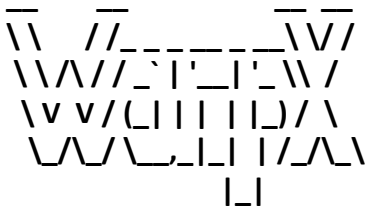

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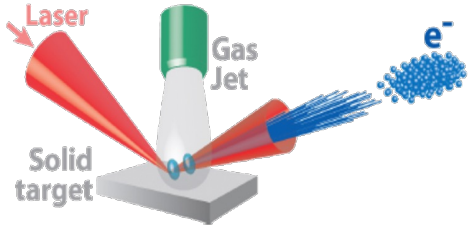

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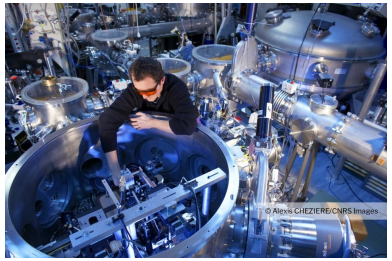
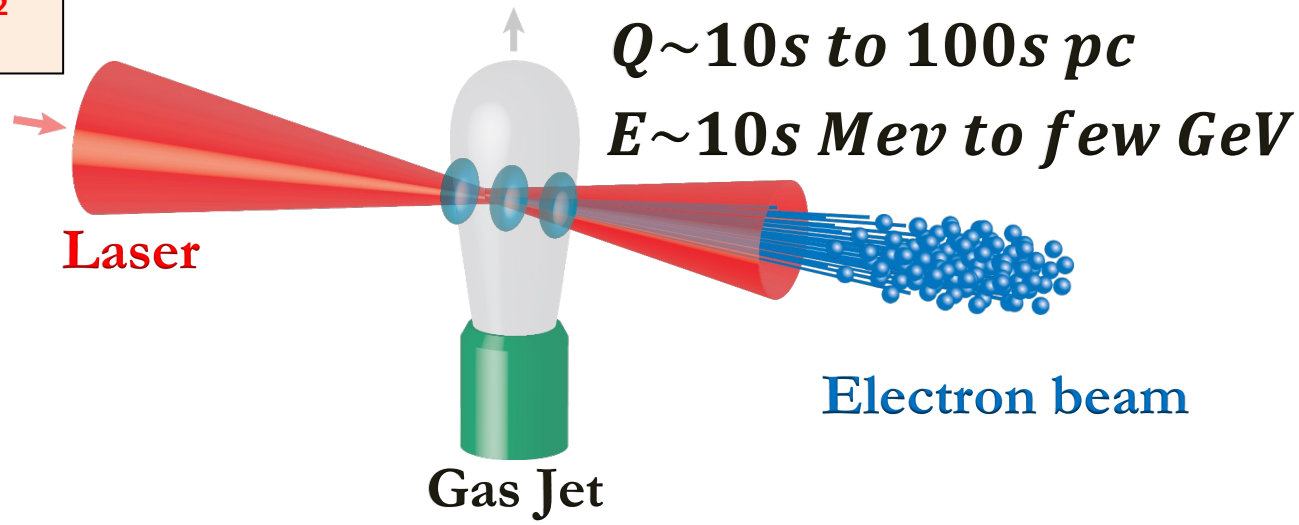


Experimental validation

The laser wakefield acceleration acceleration provides compact & energetic electron sources, but the charge is typically low….

$I \sim 10^{18\text{-}19}\ W/cm^2$

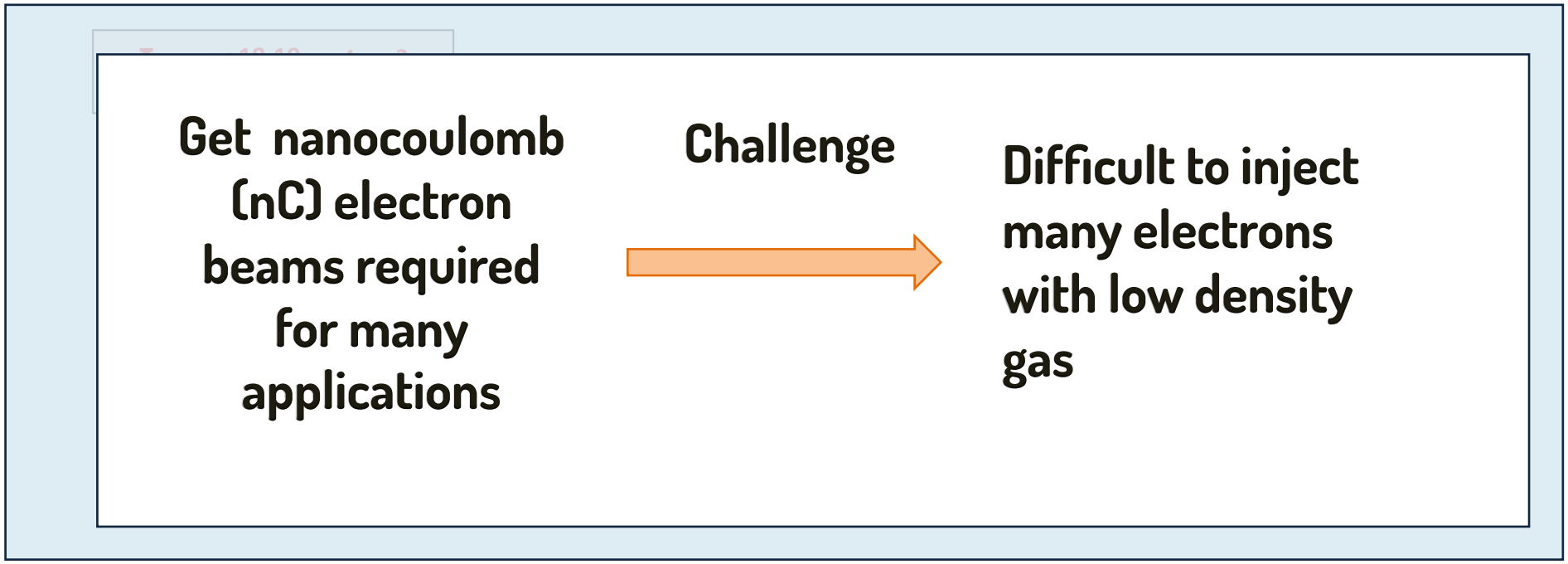


- Very compact : 8 GeV on cm

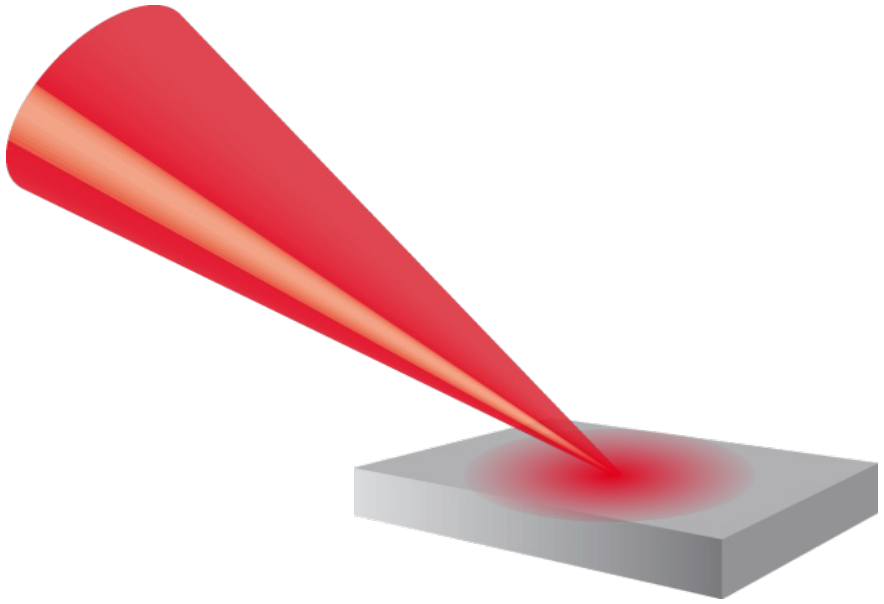
A. J. Gonsalves *et al*, PRL, 2019

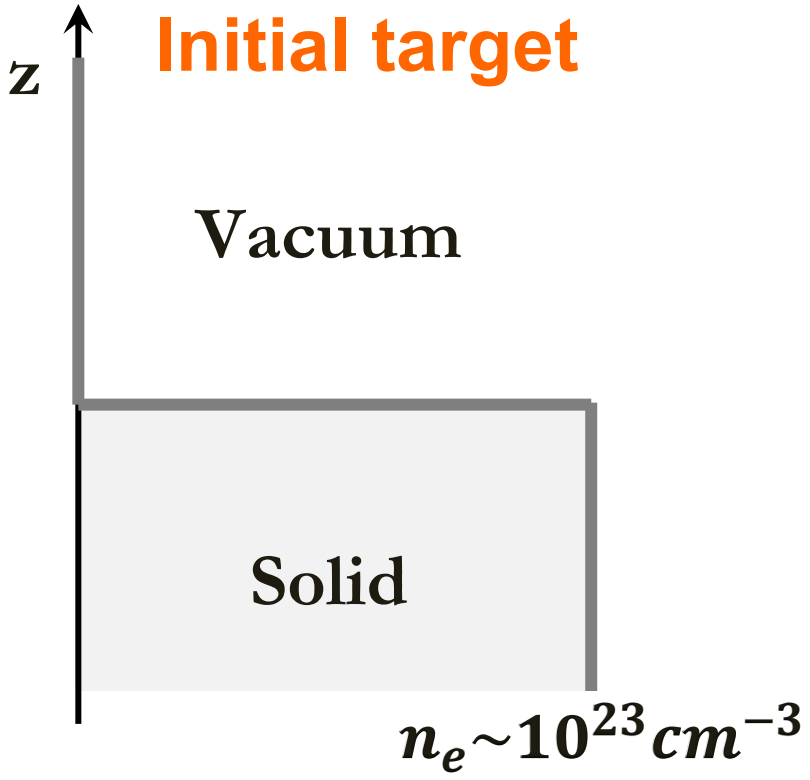
- Limitation : Provides low charge per bunch

The laser wakefield acceleration acceleration provides compact & energetic electron sources, but the charge is typically low….



‘Plasma mirrors’ can be high-charge electron sources





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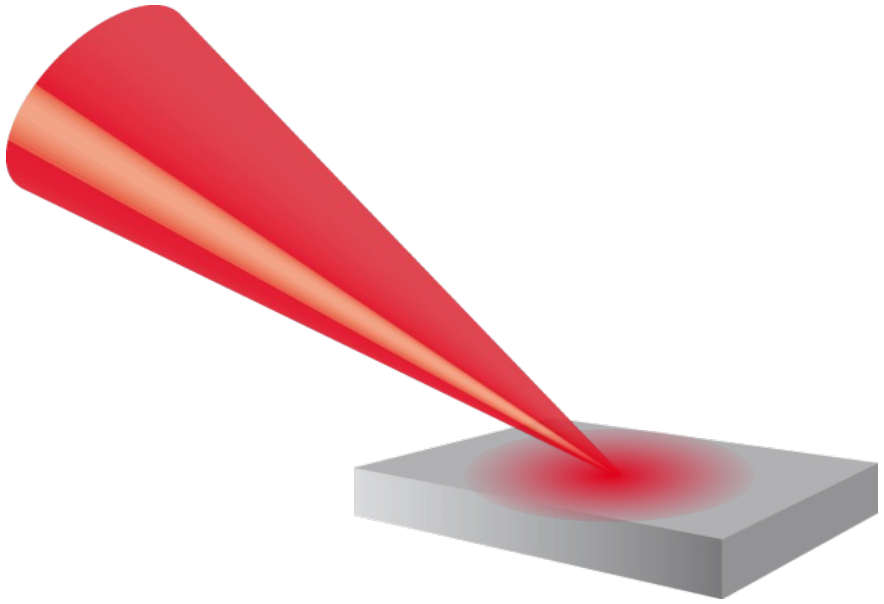

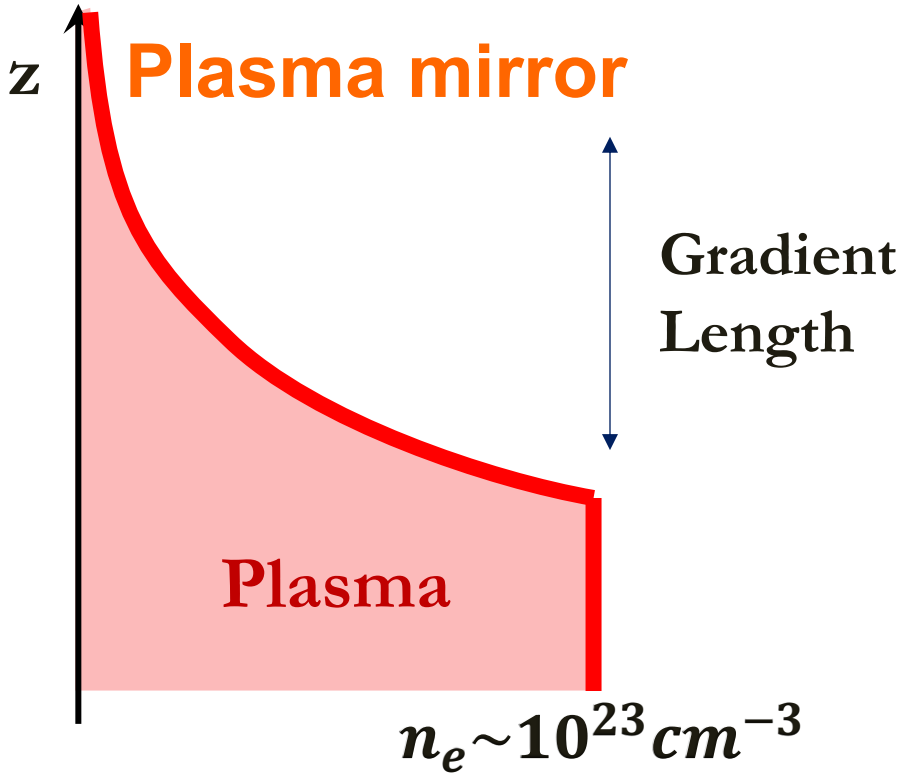

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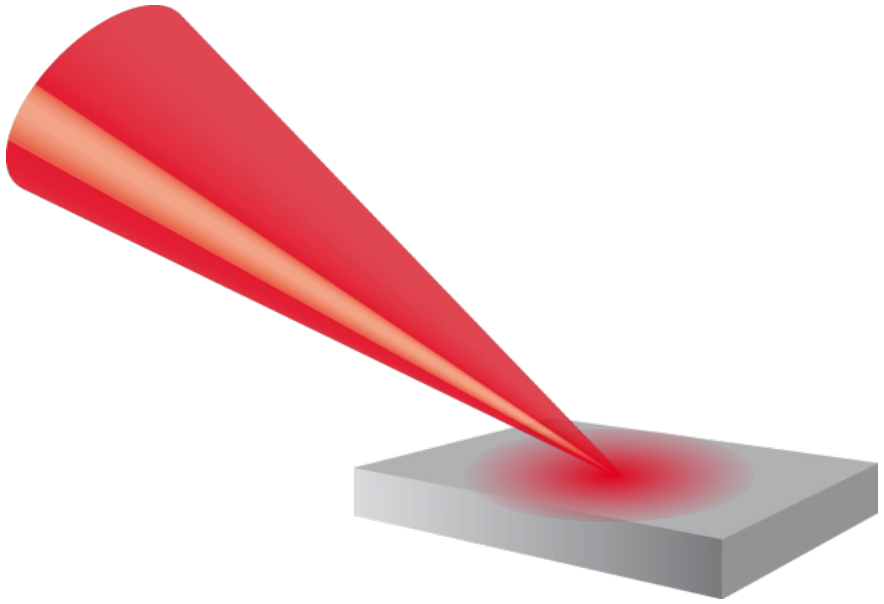
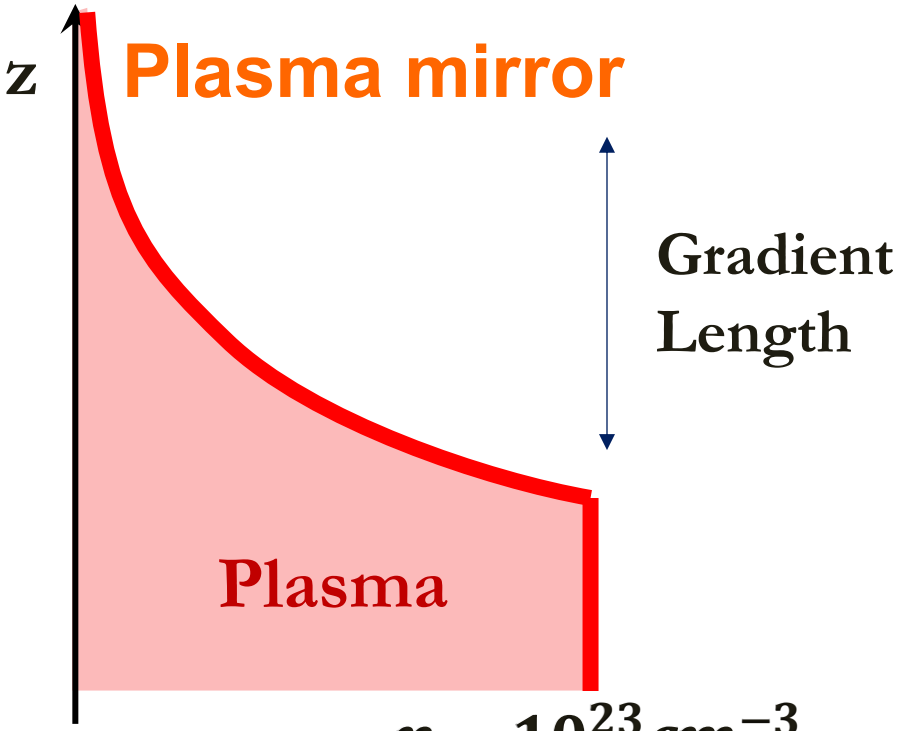
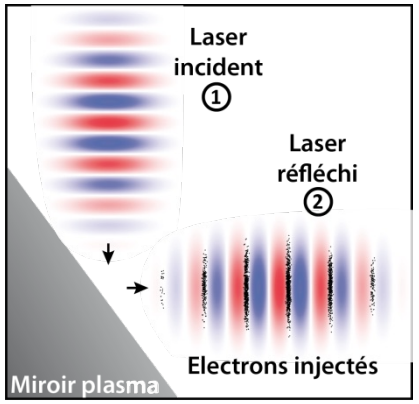
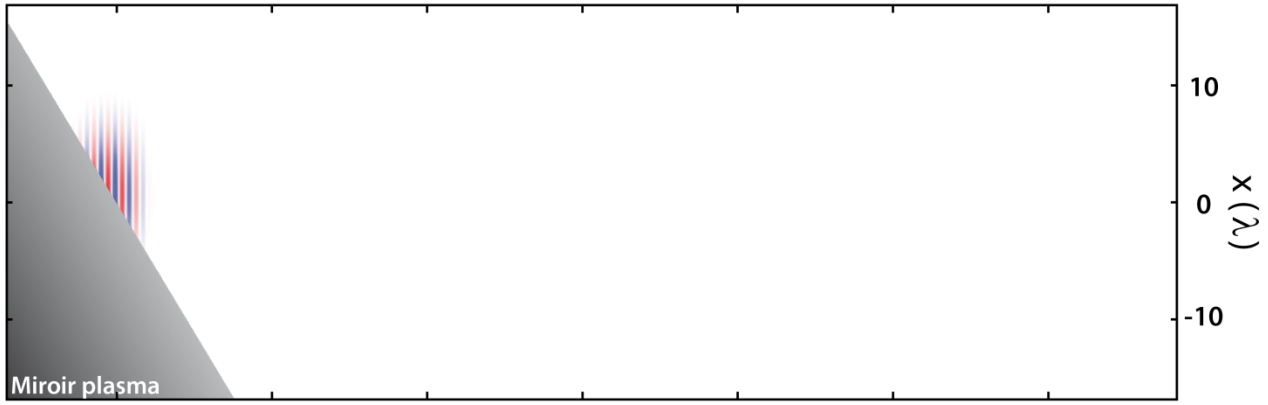






Simulation PIC



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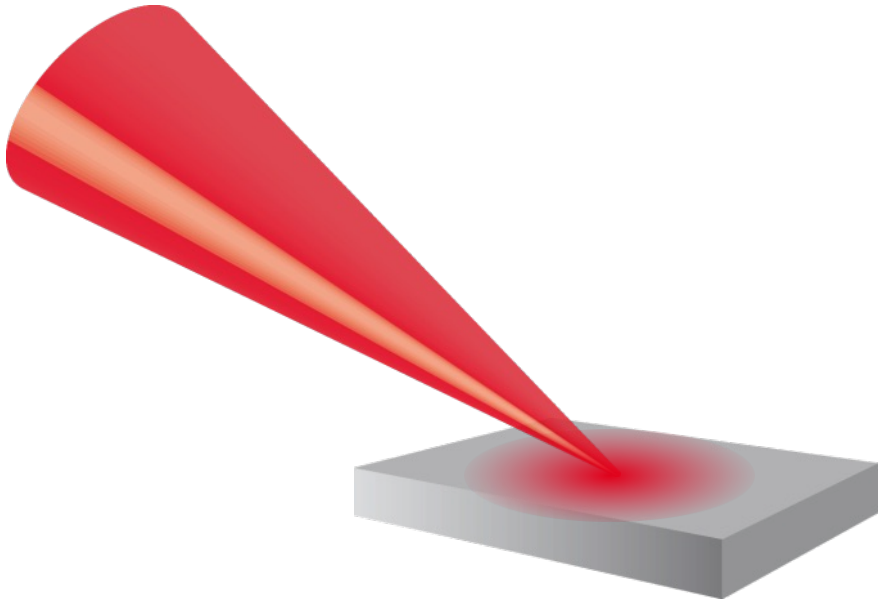

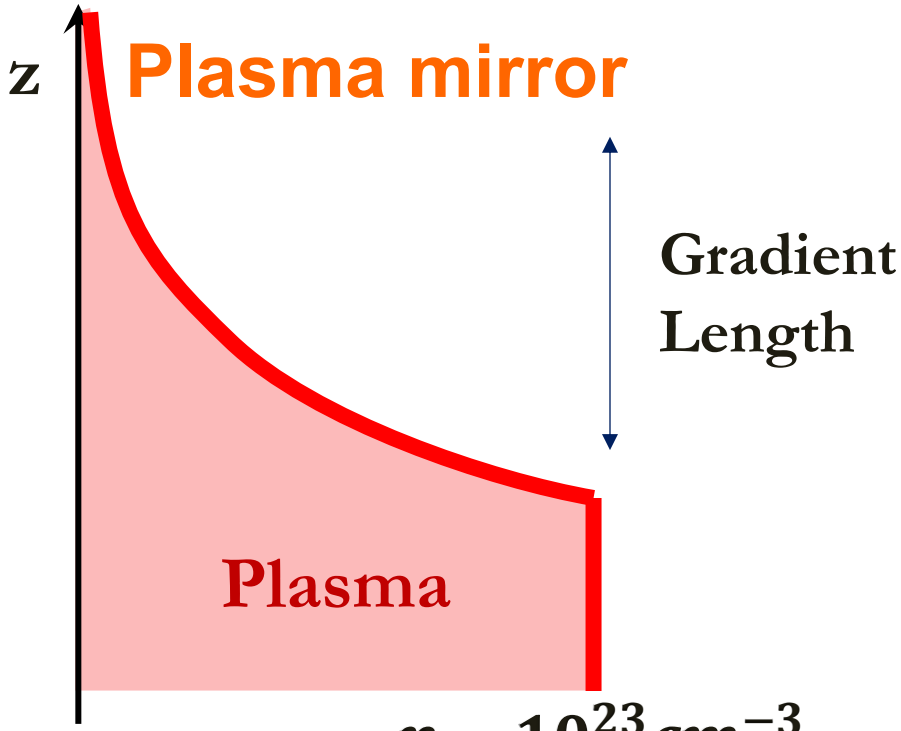

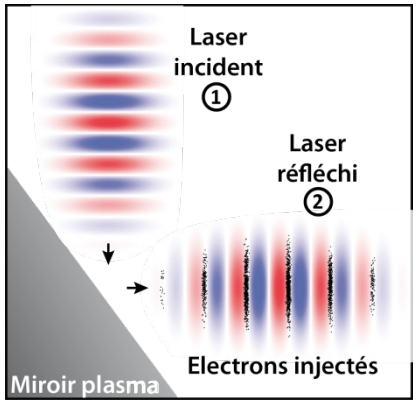

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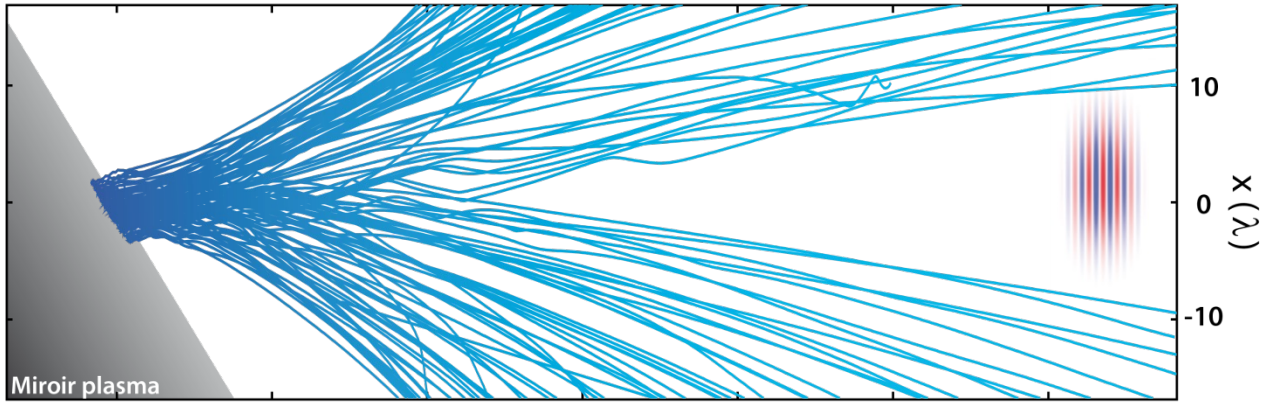

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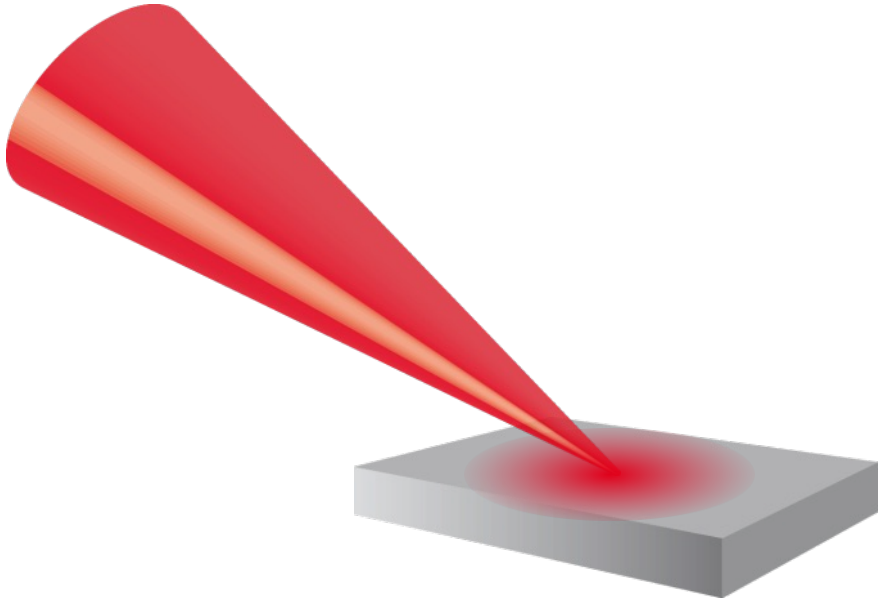
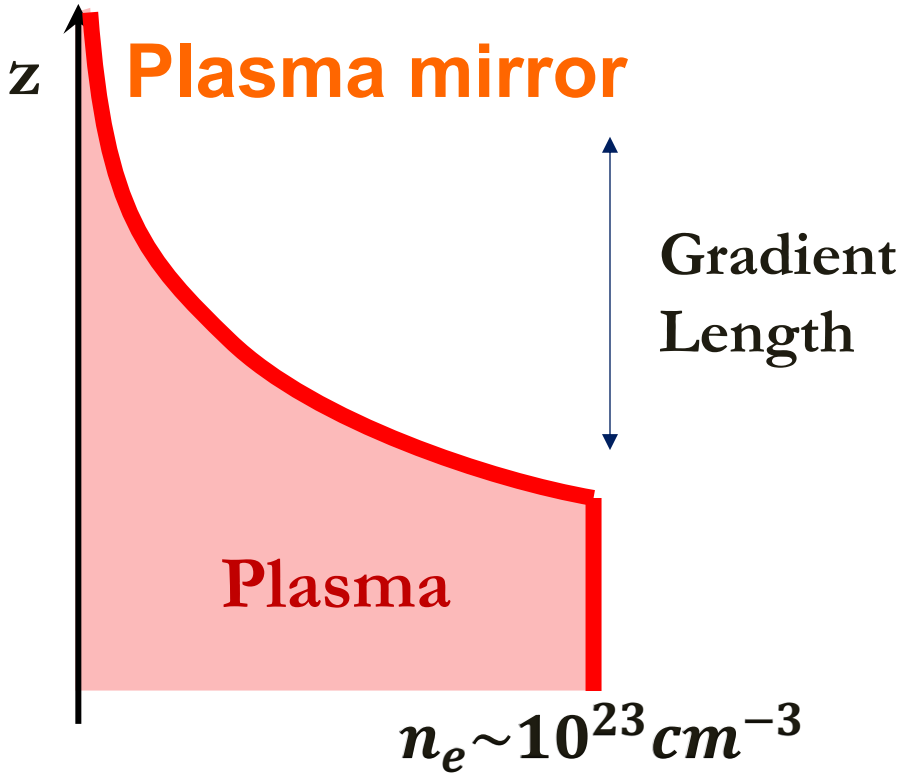


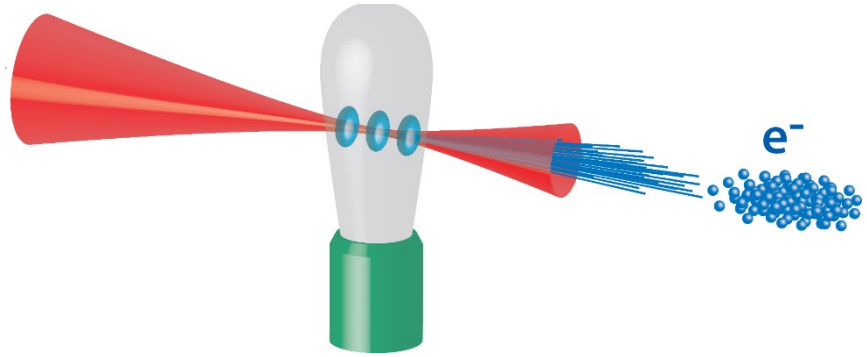


- **Provides high charge (~ nC)**

M. Thévenet et al, Nature physics, 2015

Where does the idea of the Hybrid Target comes from ?

Electron acceleration in gas



- Low charge : 10s to 100s pC

But

- ✓ High energy : 100s Mev to GeV
- ✓ Low divergence

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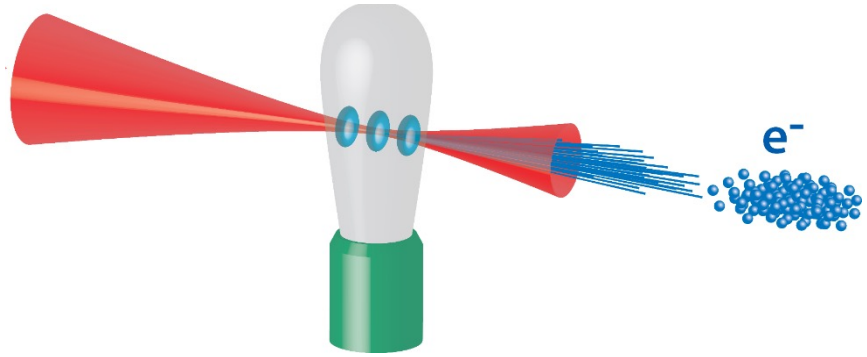

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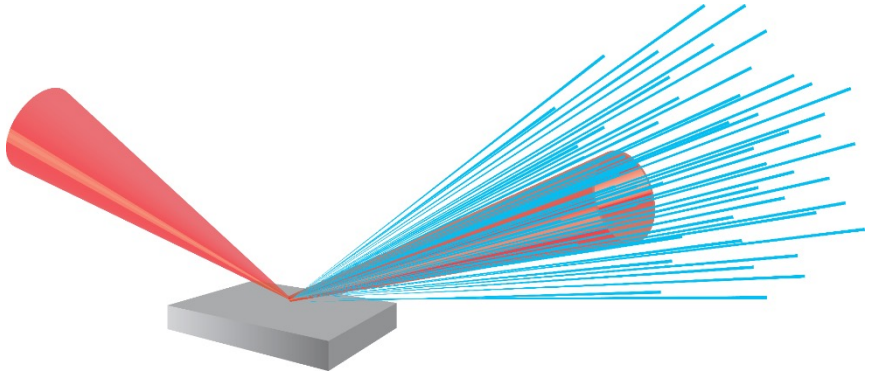
Electron acceleration with a plasma mirror



- ✓ High charge

But

- Low energy : 10 MeV
- High divergence

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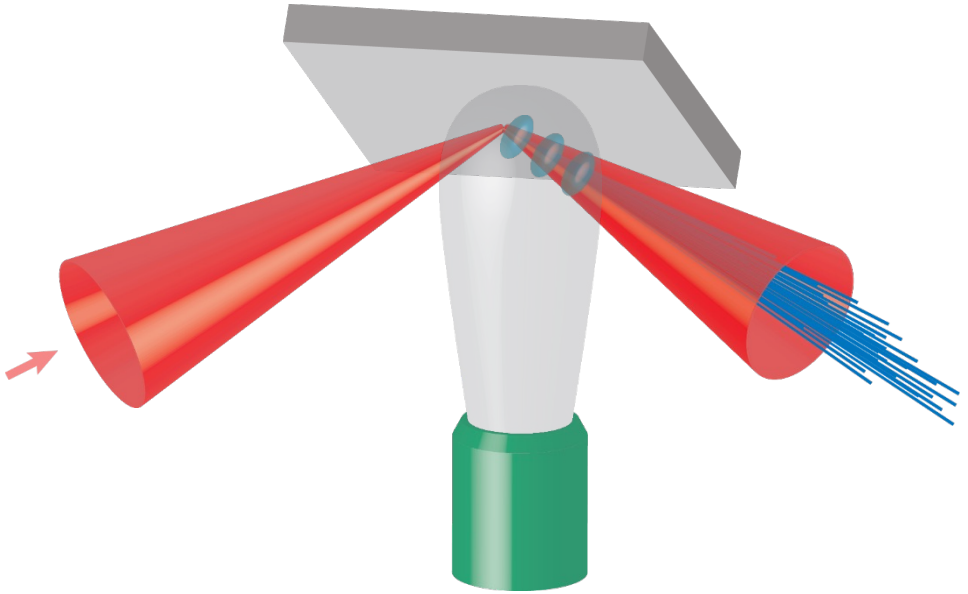
A two-step process :

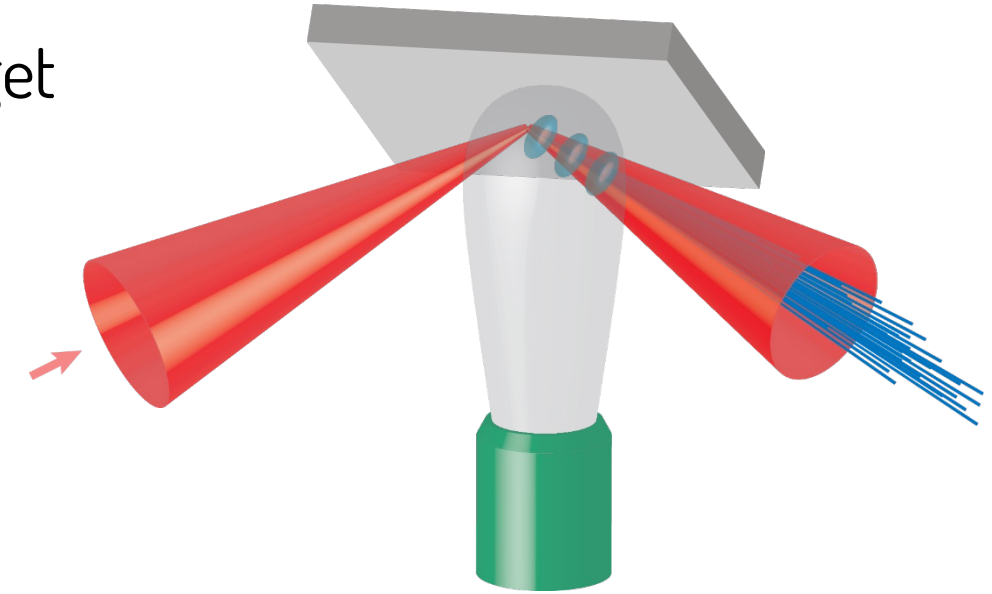


Where does the idea of the Hybrid Target comes from ?

A two-step process :

1) Injection from the solid target

2) Acceleration in the gas



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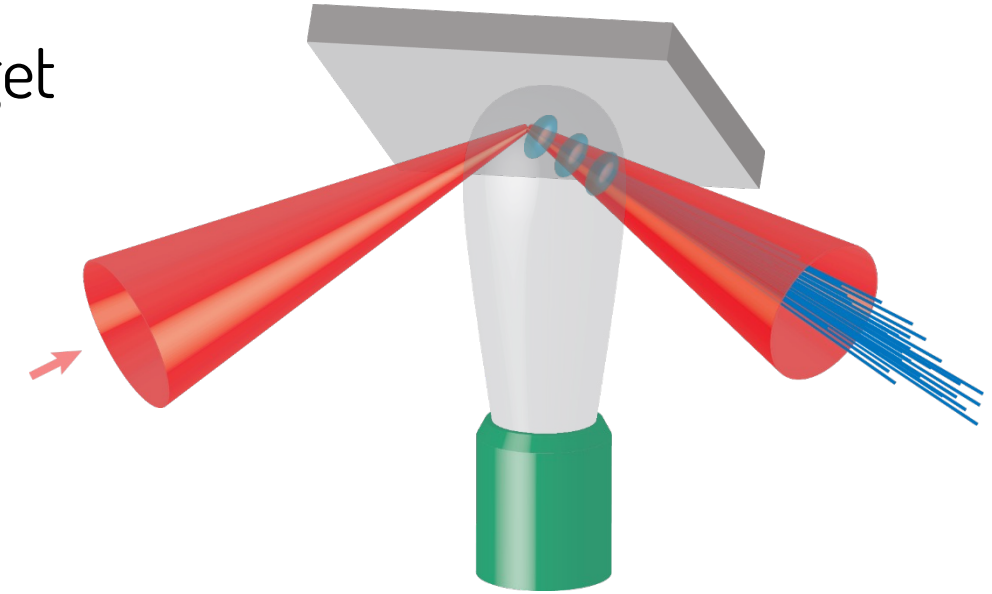
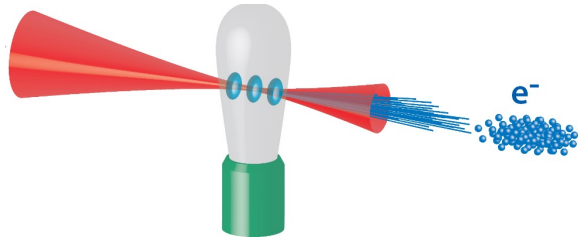


It should provide :

- ✓ A high charge from the high density of the solid target
- ✓ A high quality since the injection is localized at solid surface

Outline



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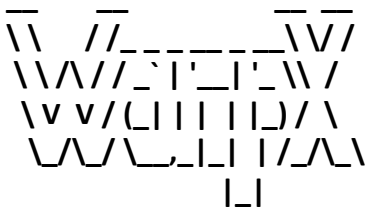
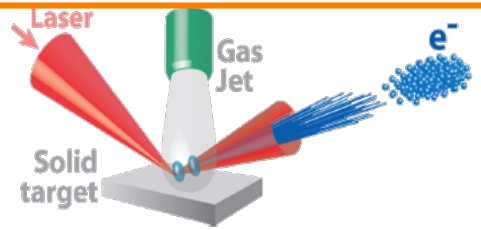
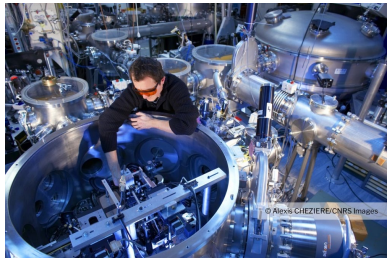


WarpX : an exascale PIC code



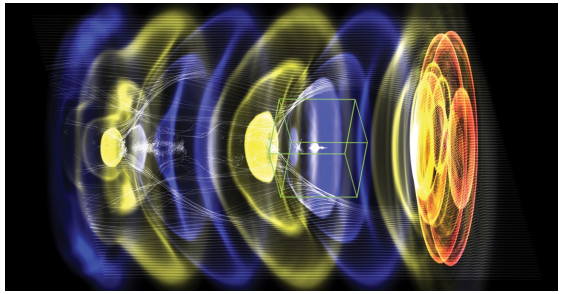
Numerical study



Experimental validation

WarpX is an open-source Particle-In-Cell code for the exascale era.

30+ contributors



EXASCALE COMPUTING PROJECT

BERKELEY LAB

DE LA RECHERCHE À L'INDUSTRIE

Lawrence Livermore National Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

DESY.

CERN

MODERN ELECTRON

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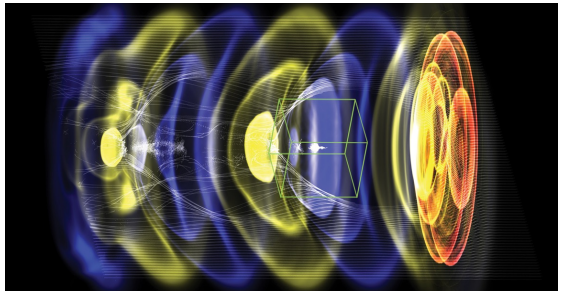

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open source initiative Approved License®

Open-source & available on Github

Documentation: **ecp-warpx.github.io/**

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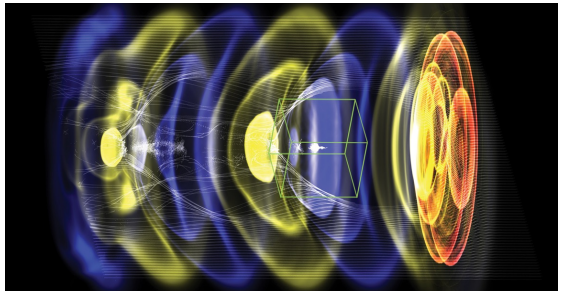

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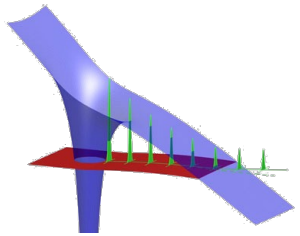
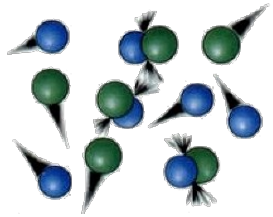
mac OS

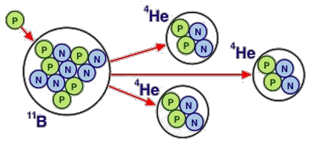
WarpX offers a comprehensive set of additional physical modules



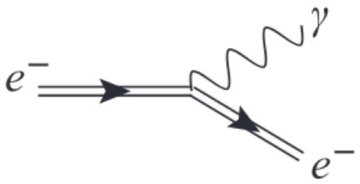
We implement **tunnel ionization** (ADK theory)



We implement **Coulomb collisions** and collisions with **neutral background**

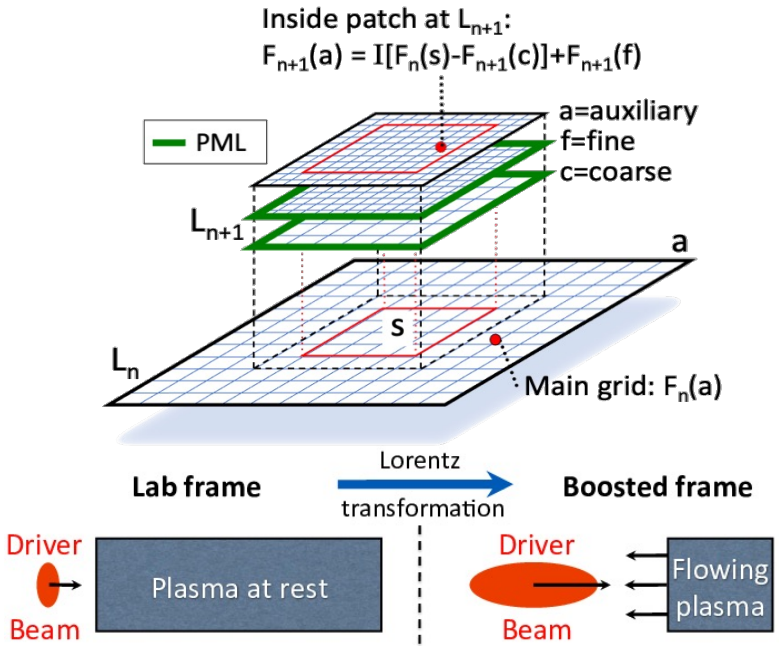


We implement **deuterium-deuterium**, **deuterium-tritium**, **deuterium-helium** and **proton-boron fusion**



We implement **quantum synchrotron** and **nonlinear Breit-Wheeler pair production**

WarpX provides advanced algorithms



We provide the option of improving the resolution in a certain region of the simulation :**"Mesh Refinement"**

We provide the option of using a **"Boosted frame"**, where the simulation may be orders of magnitude faster

(and several others!)

What does it gives in simulation ?

A movie from our 3D simulations

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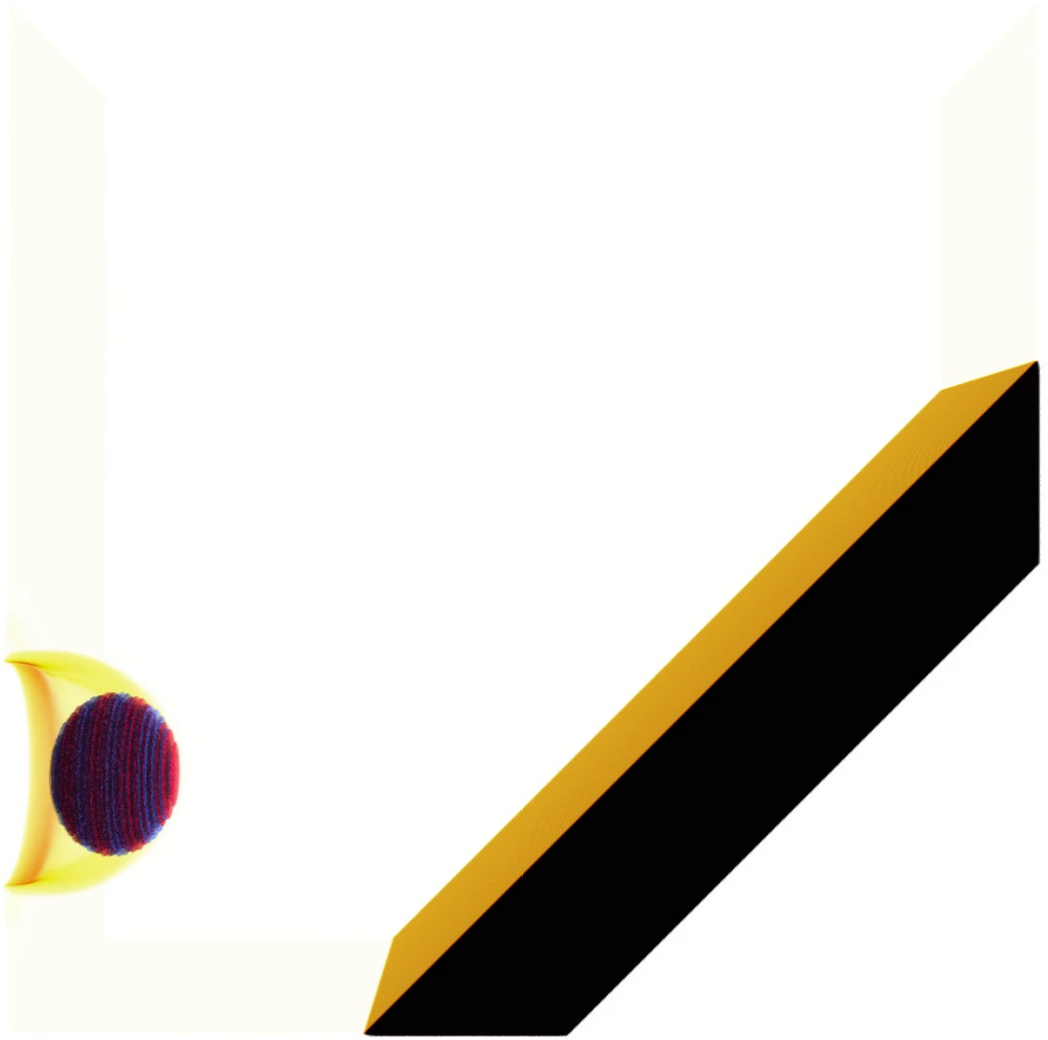

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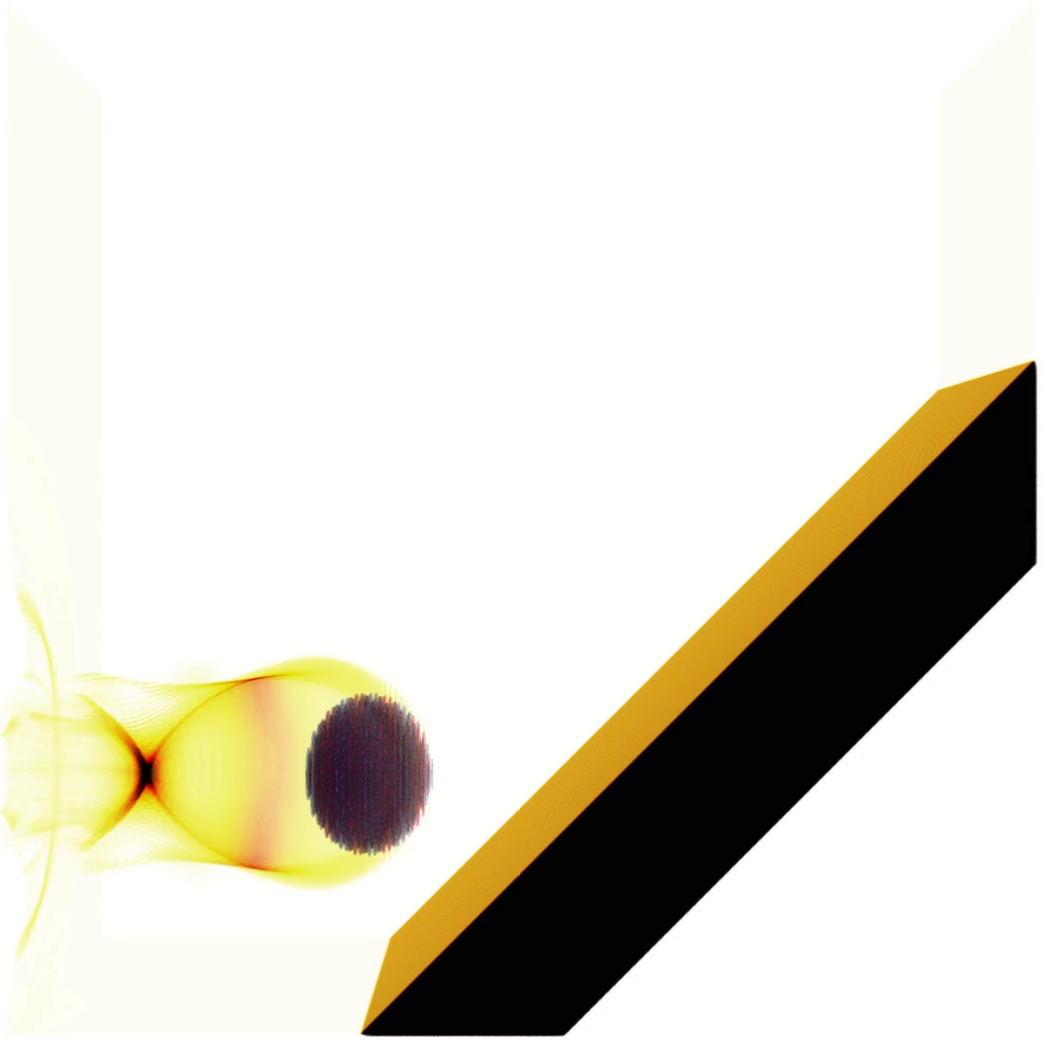

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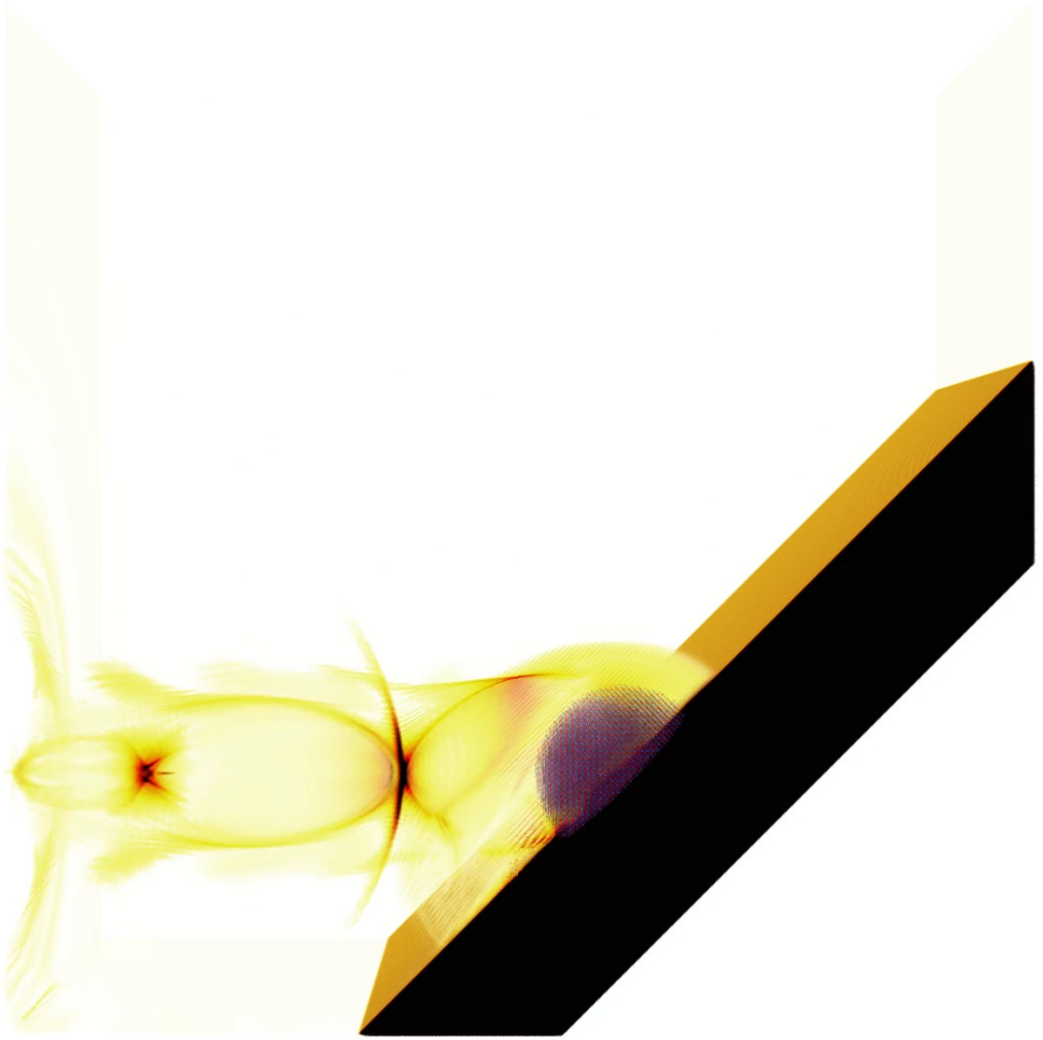

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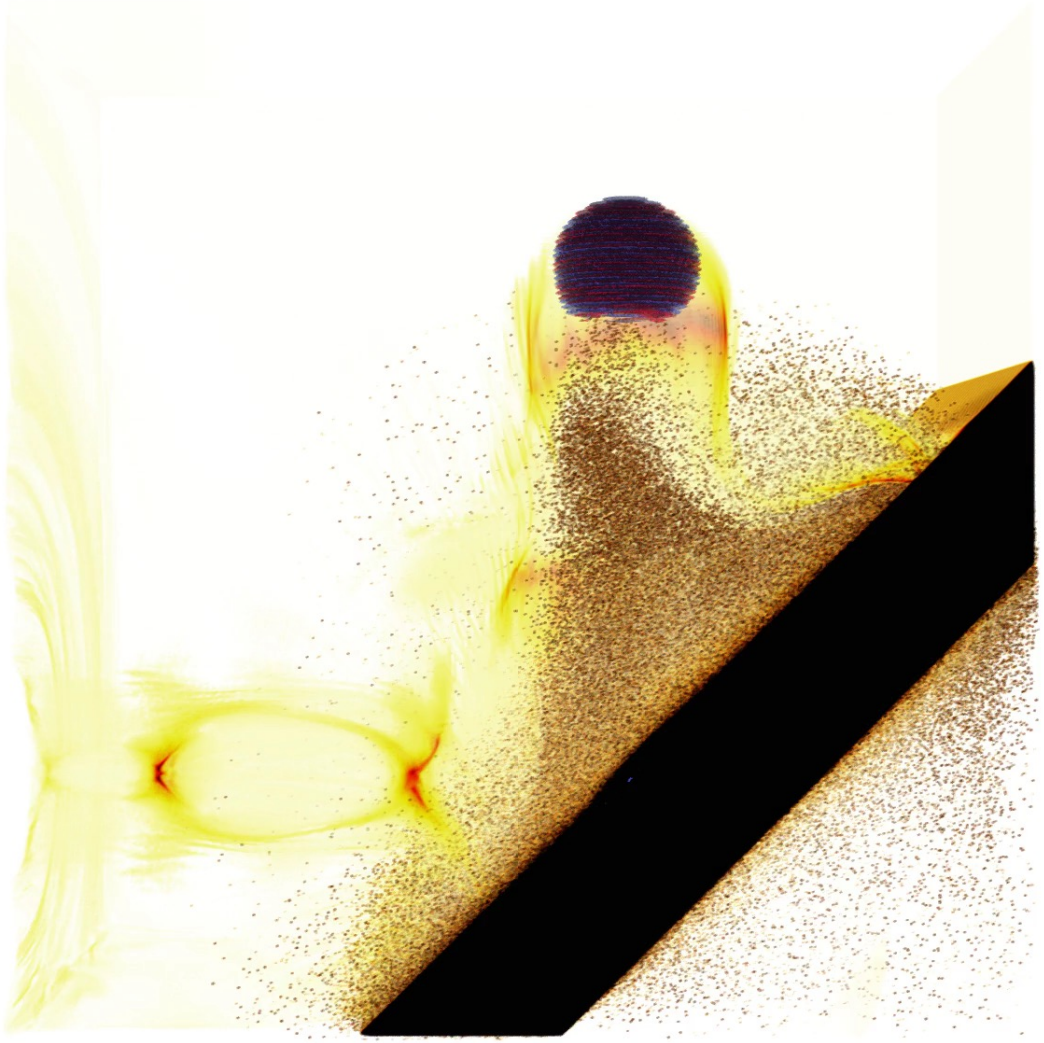

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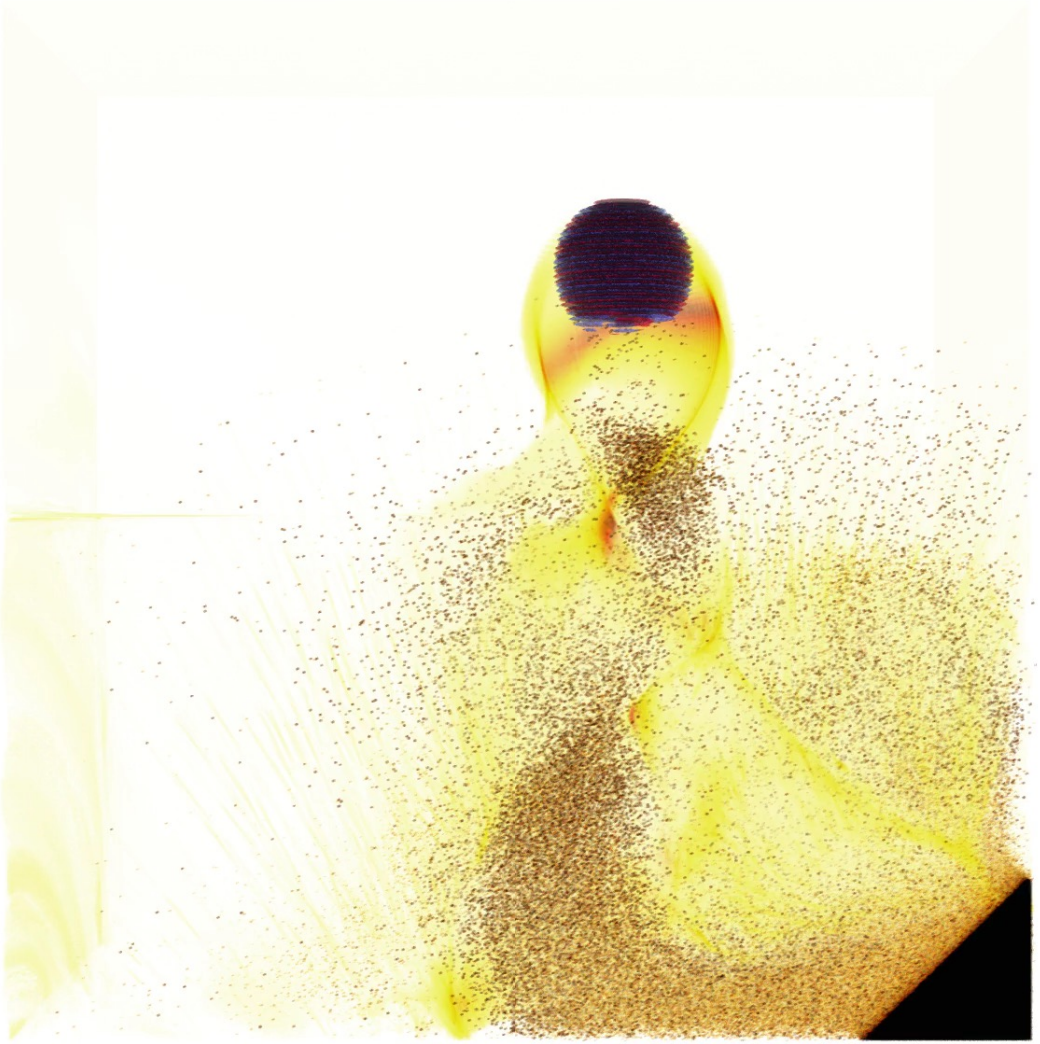

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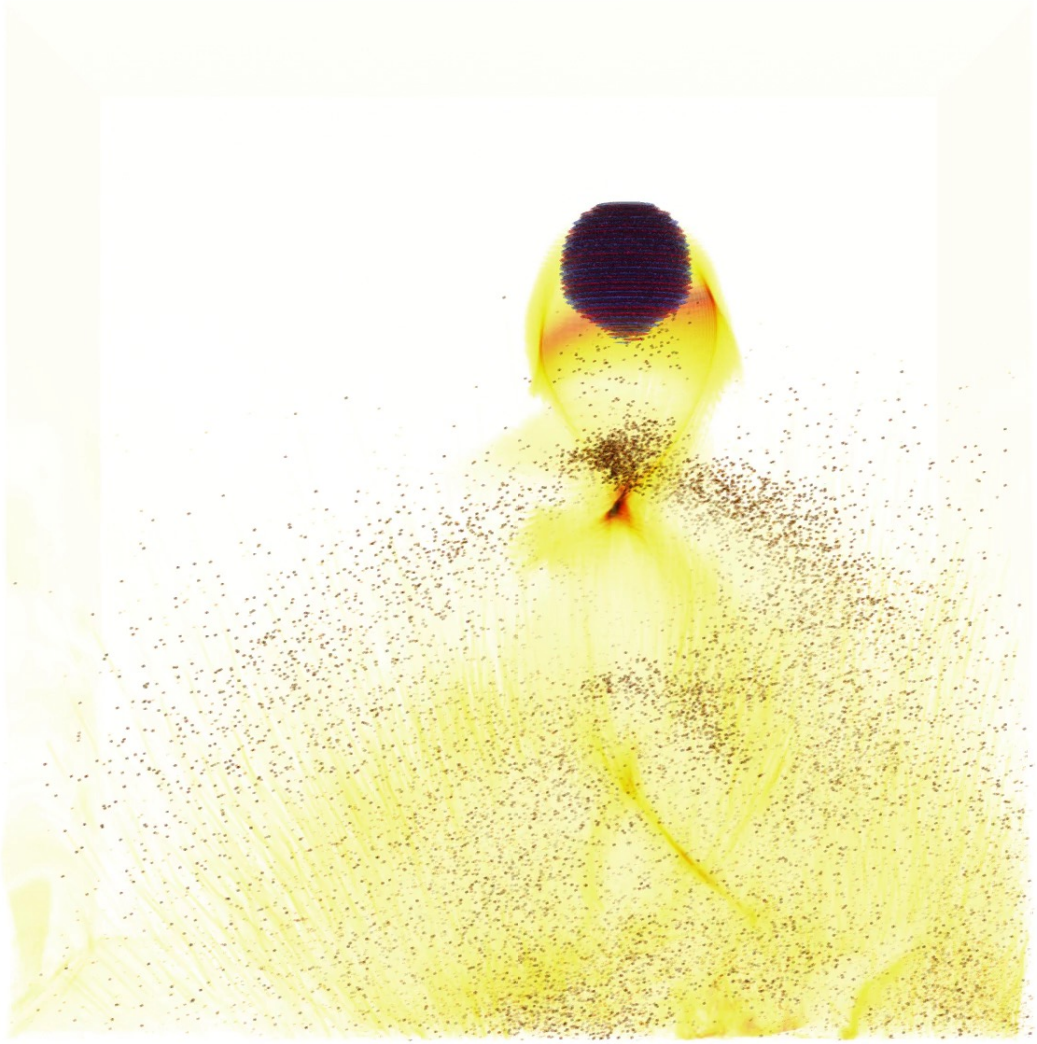

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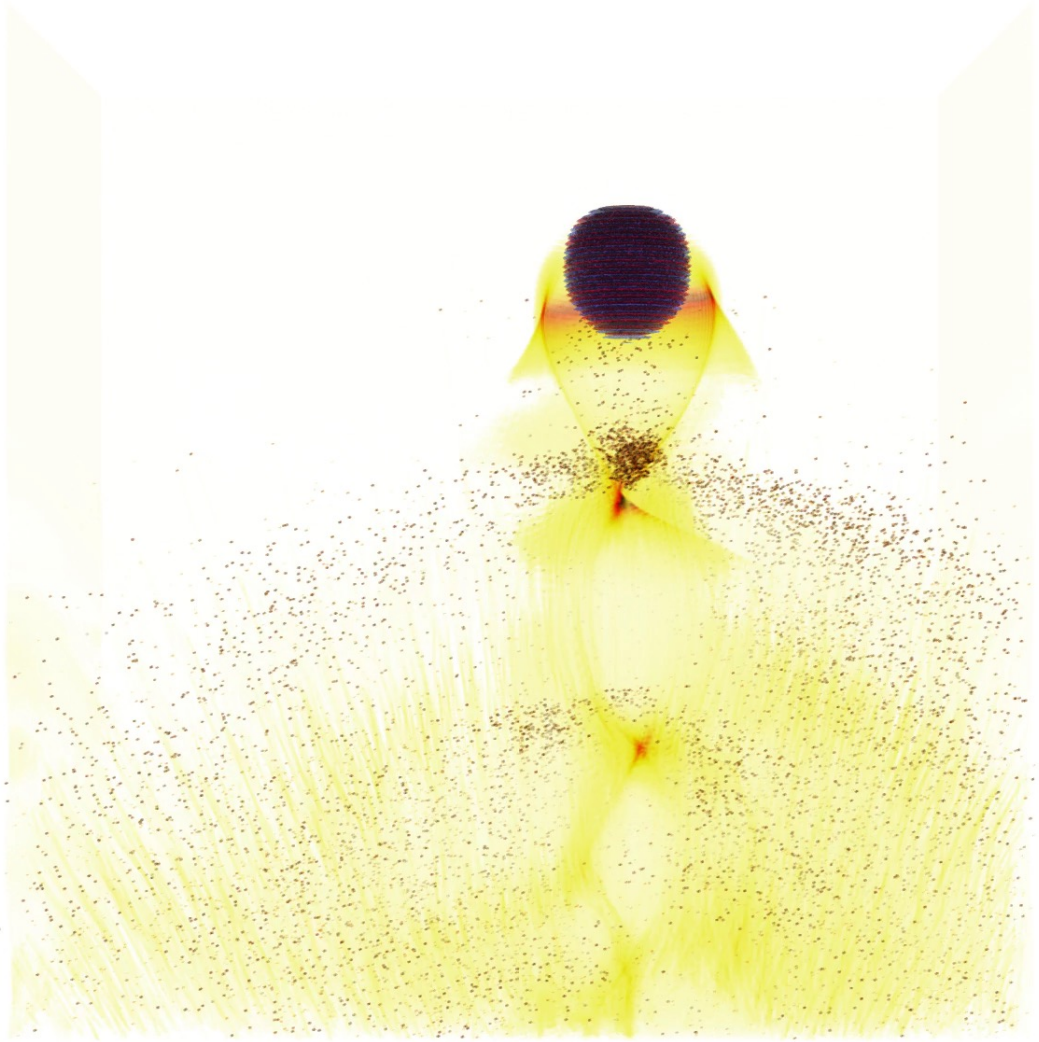

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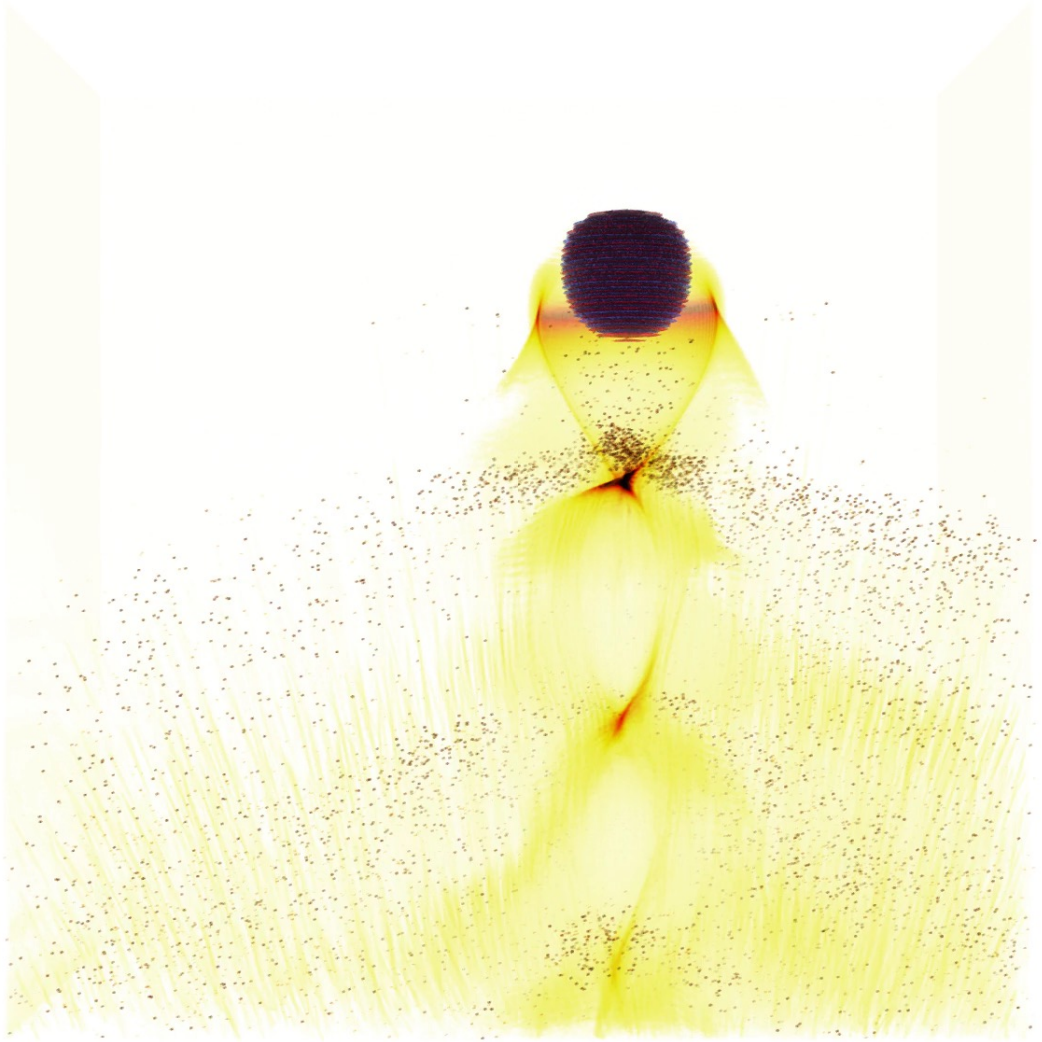

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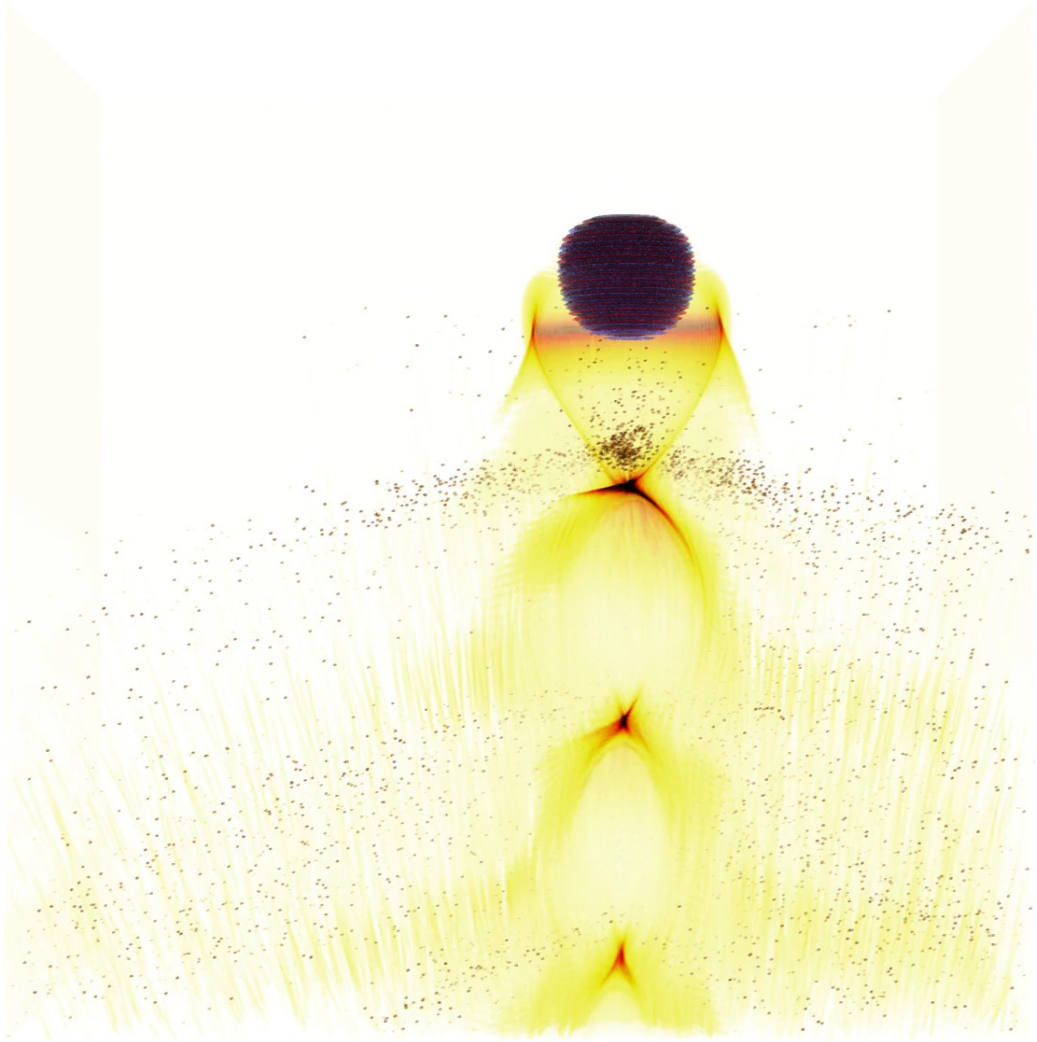
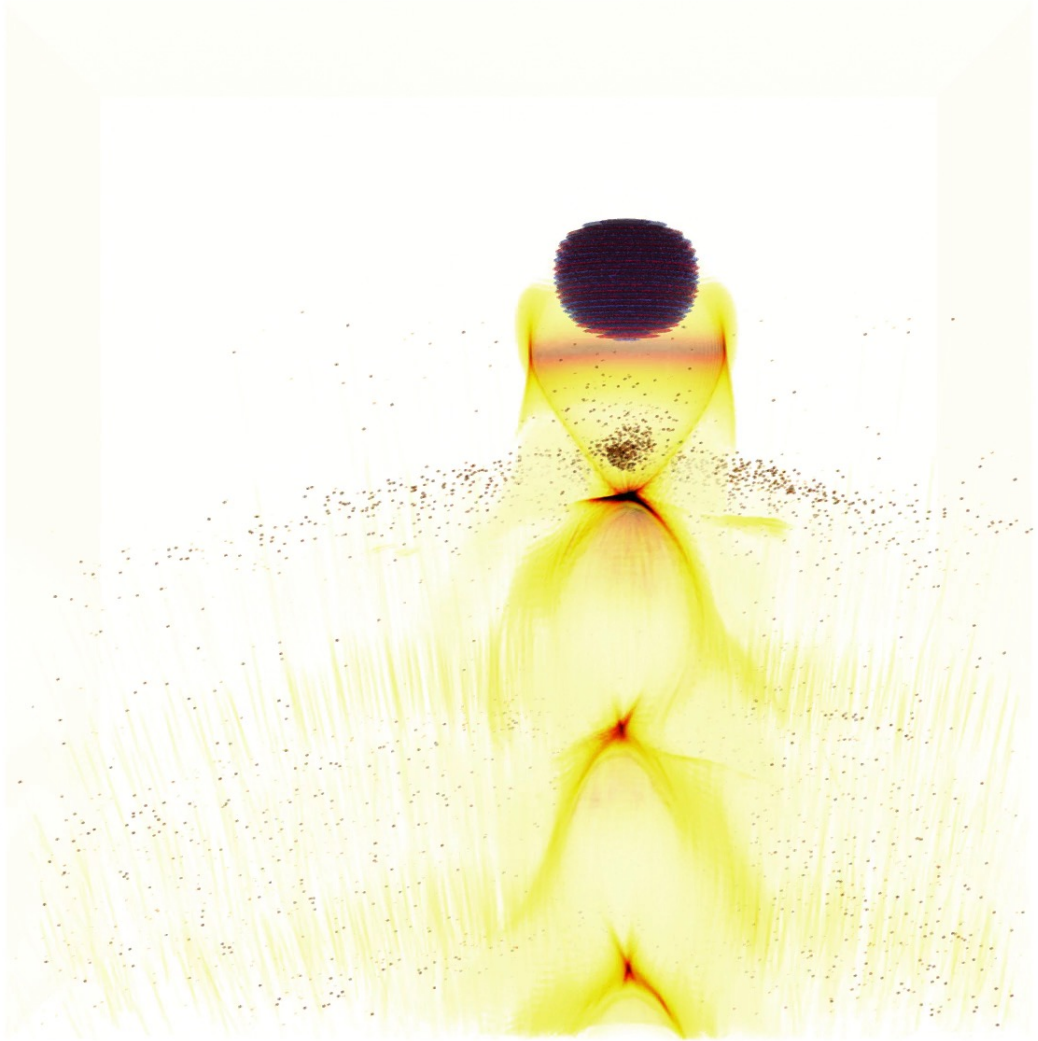
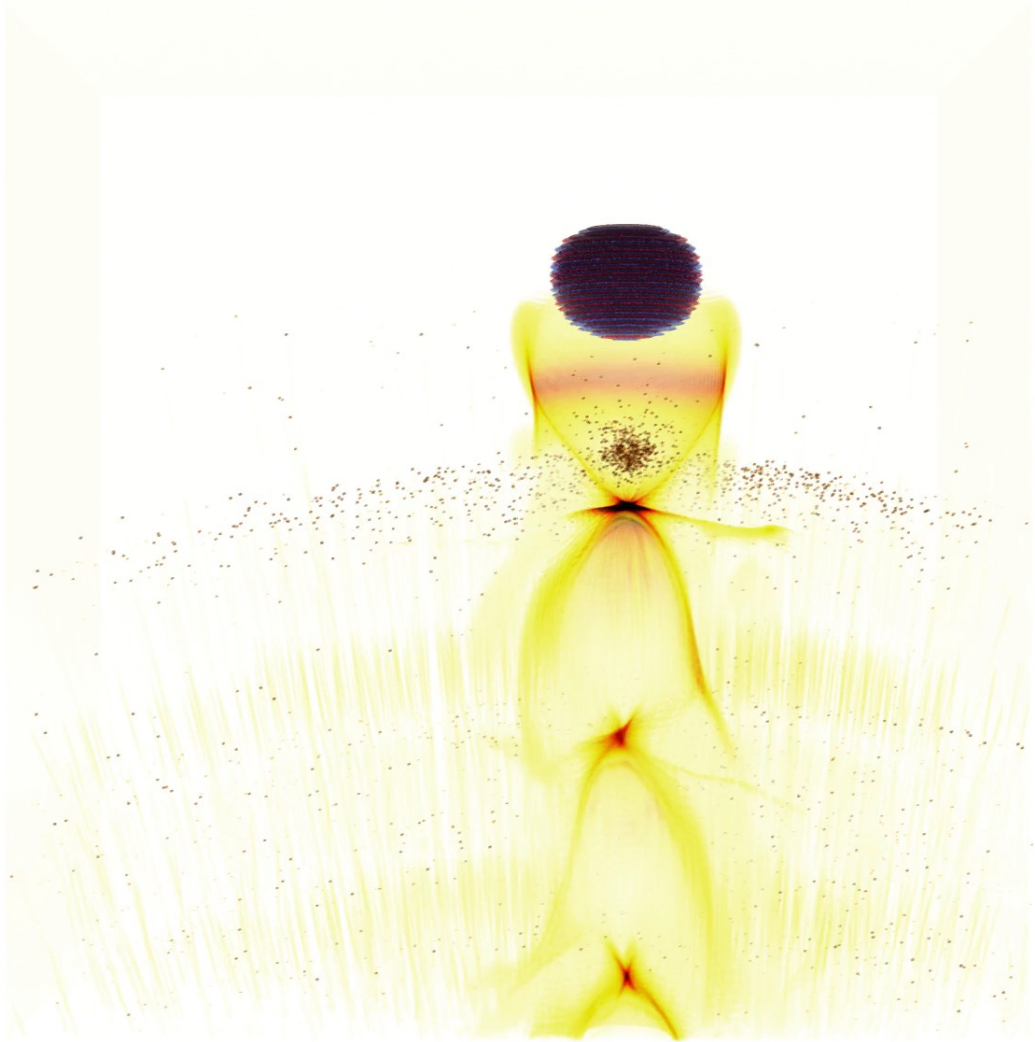


A movie from our 3D simulations

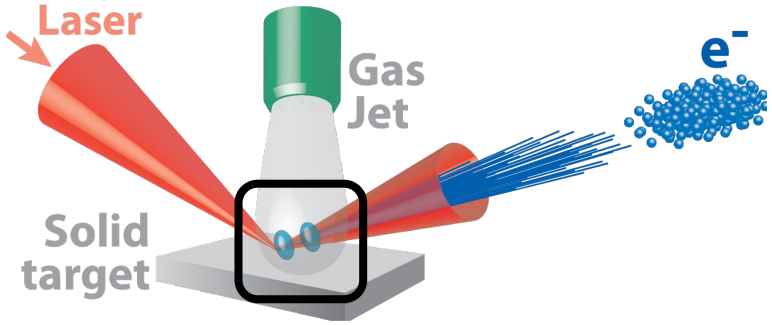


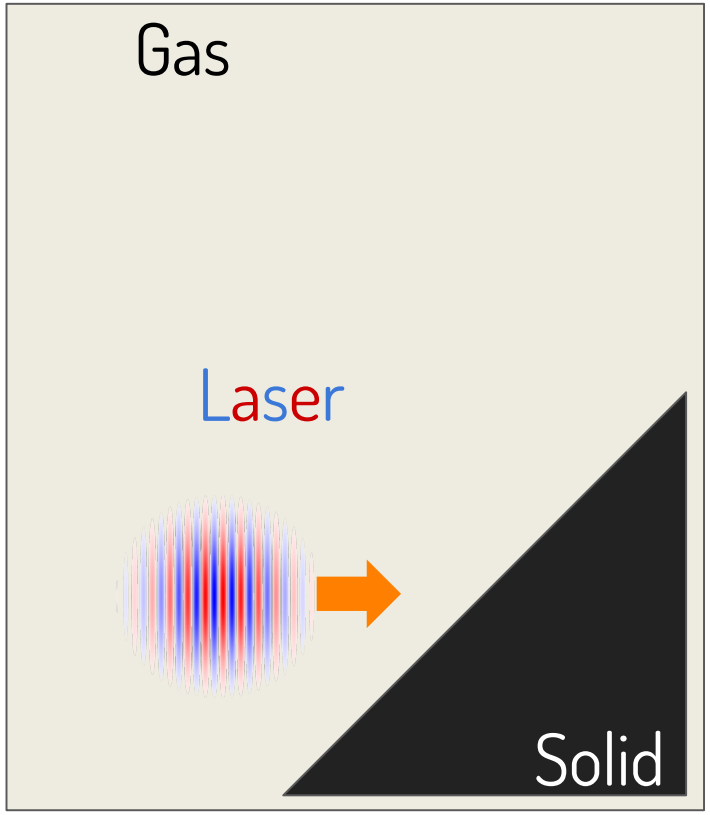
A movie from our 3D simulations



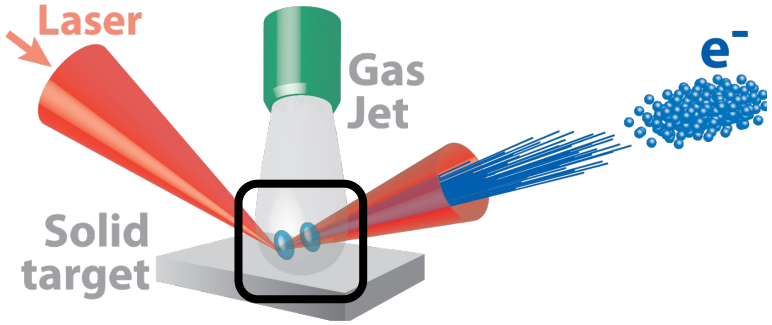
Why those simulations are challenging ?

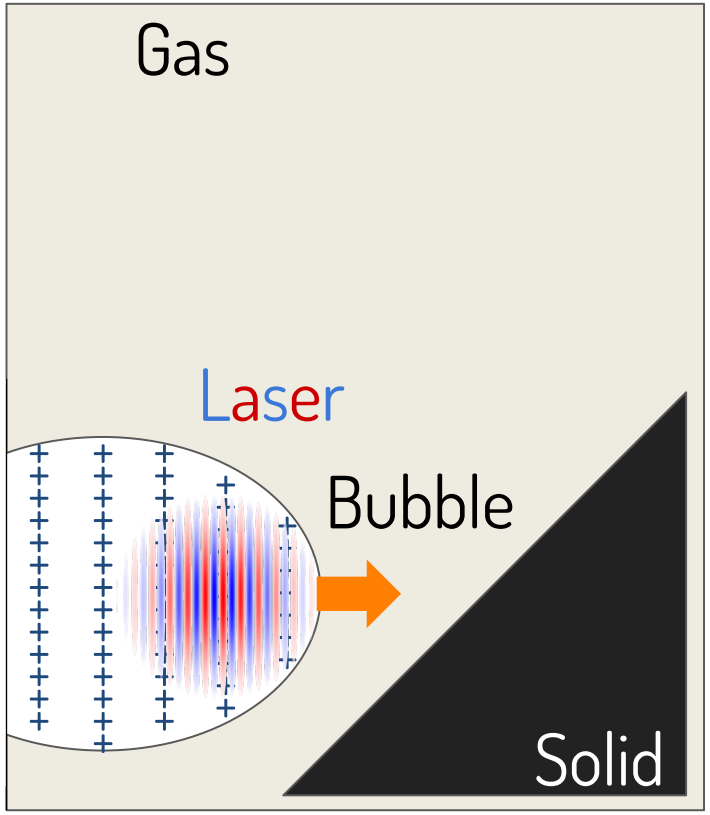
An ultra-short laser beam propagates in a low density gas



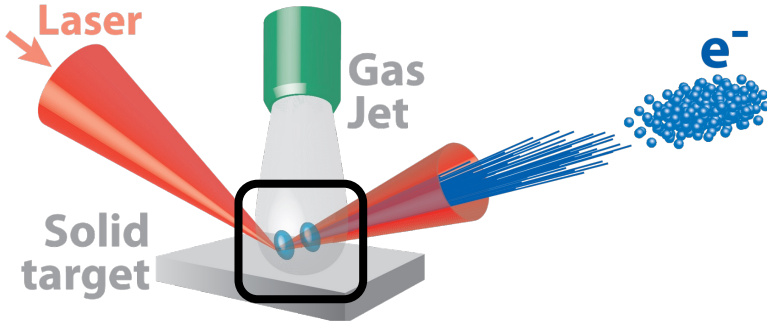


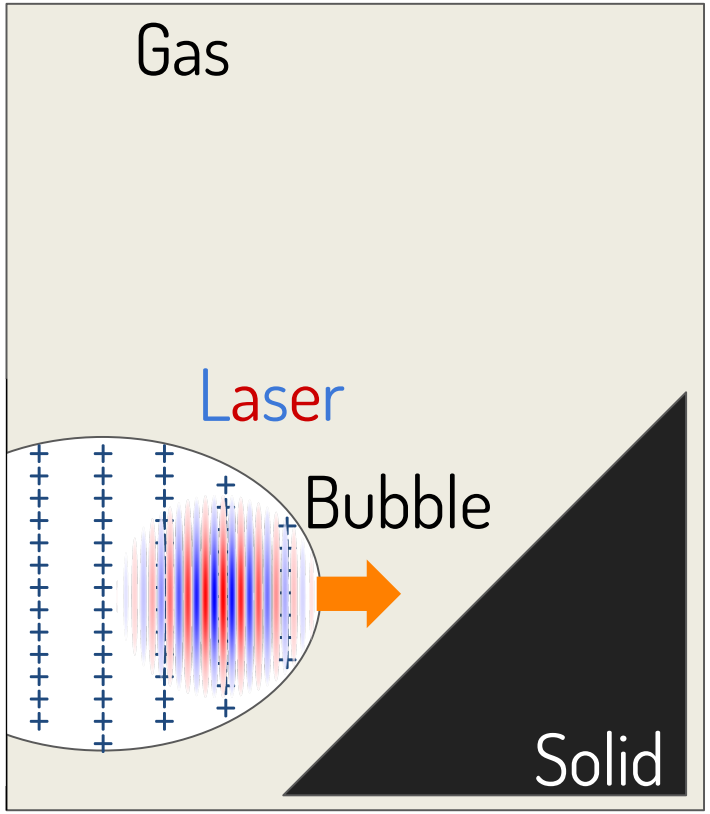
The laser pushes electrons away and generates a positively charged "bubble"

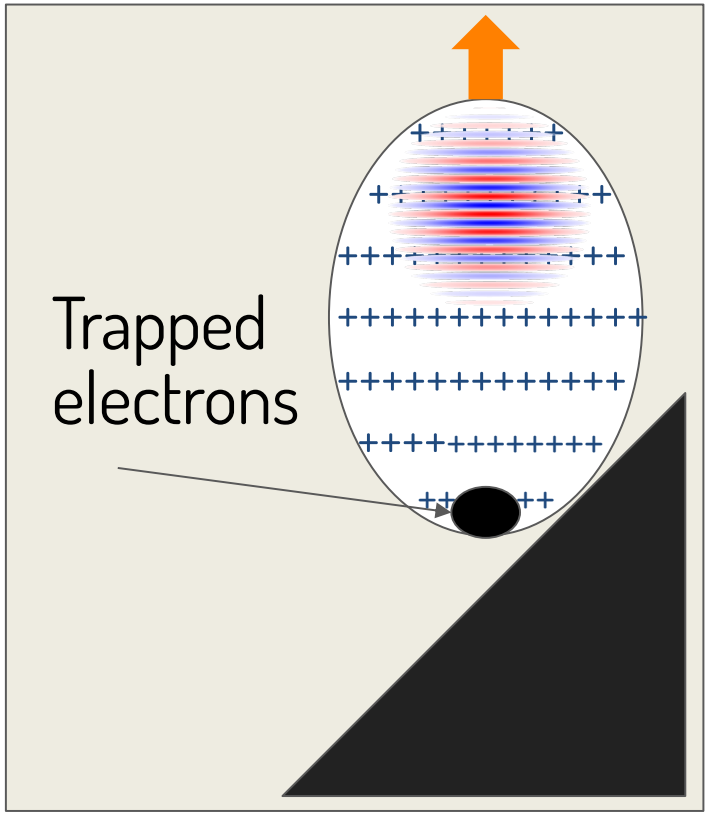




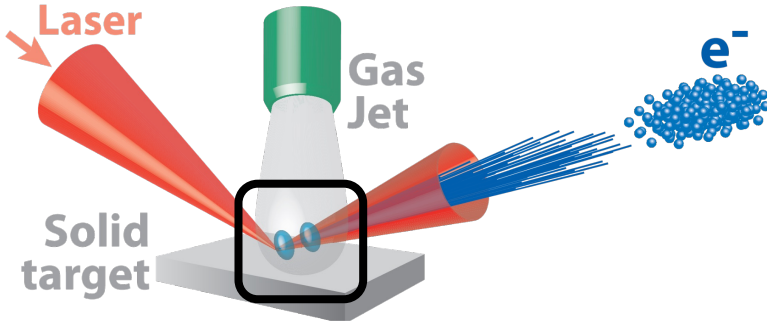
The laser is reflected by the high-density plasma and the bubble traps some of its electrons

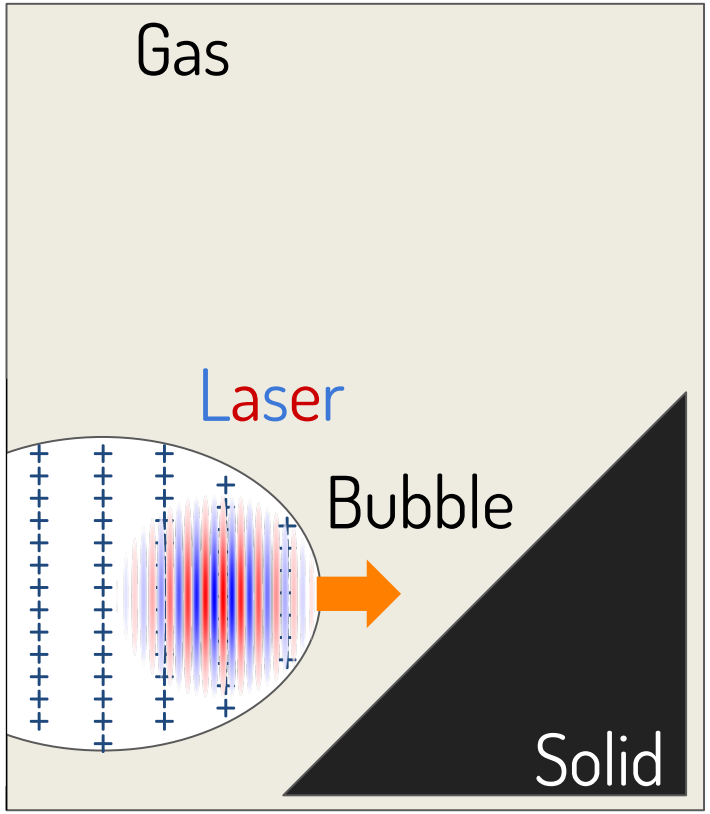


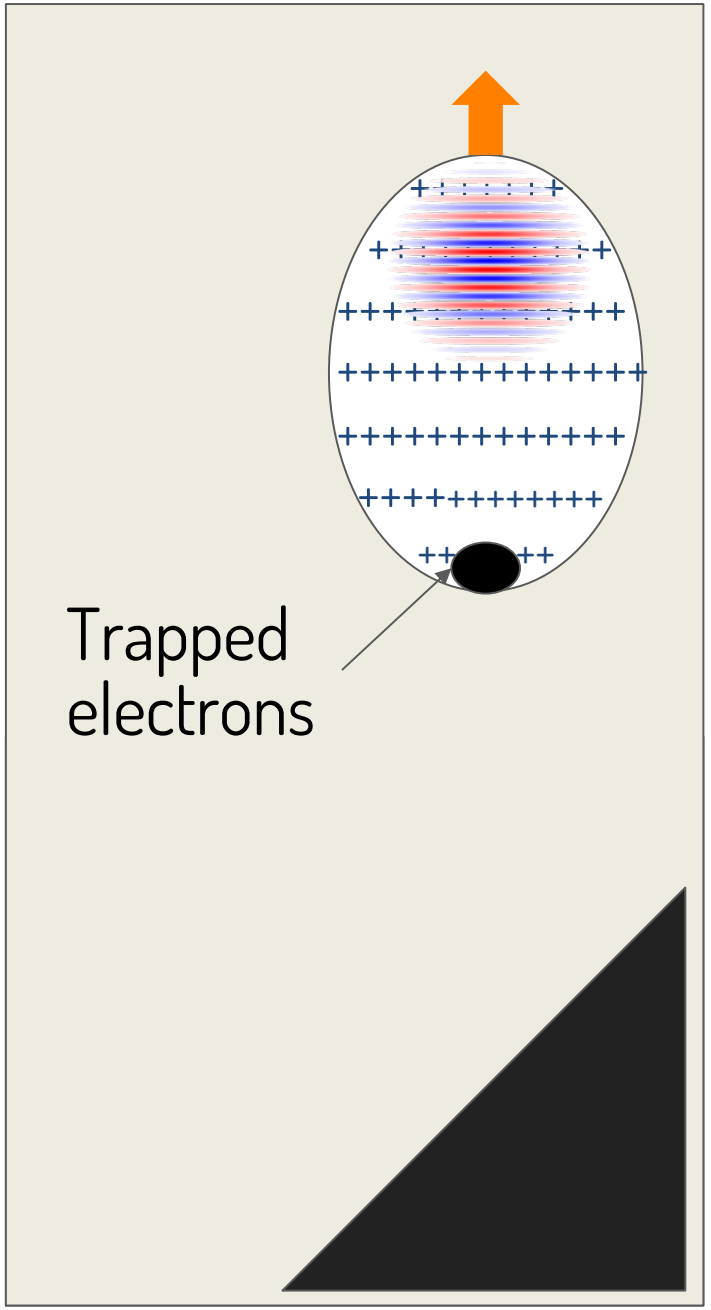




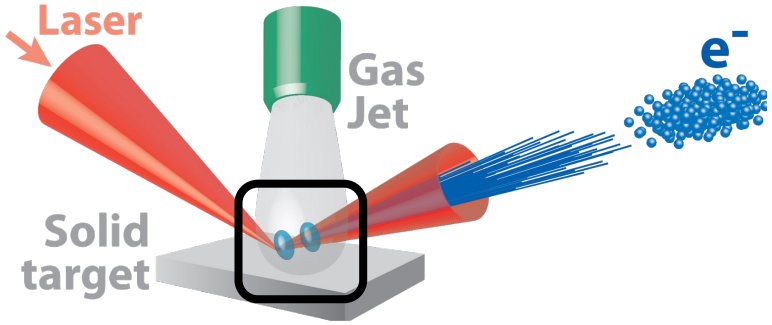
The bubble accelerates electrons over few millimeters





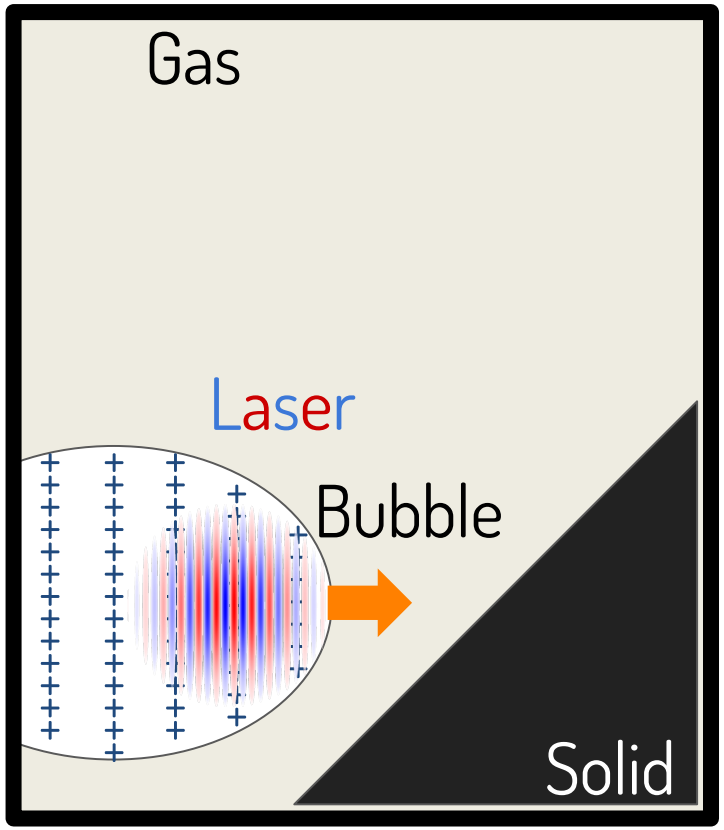


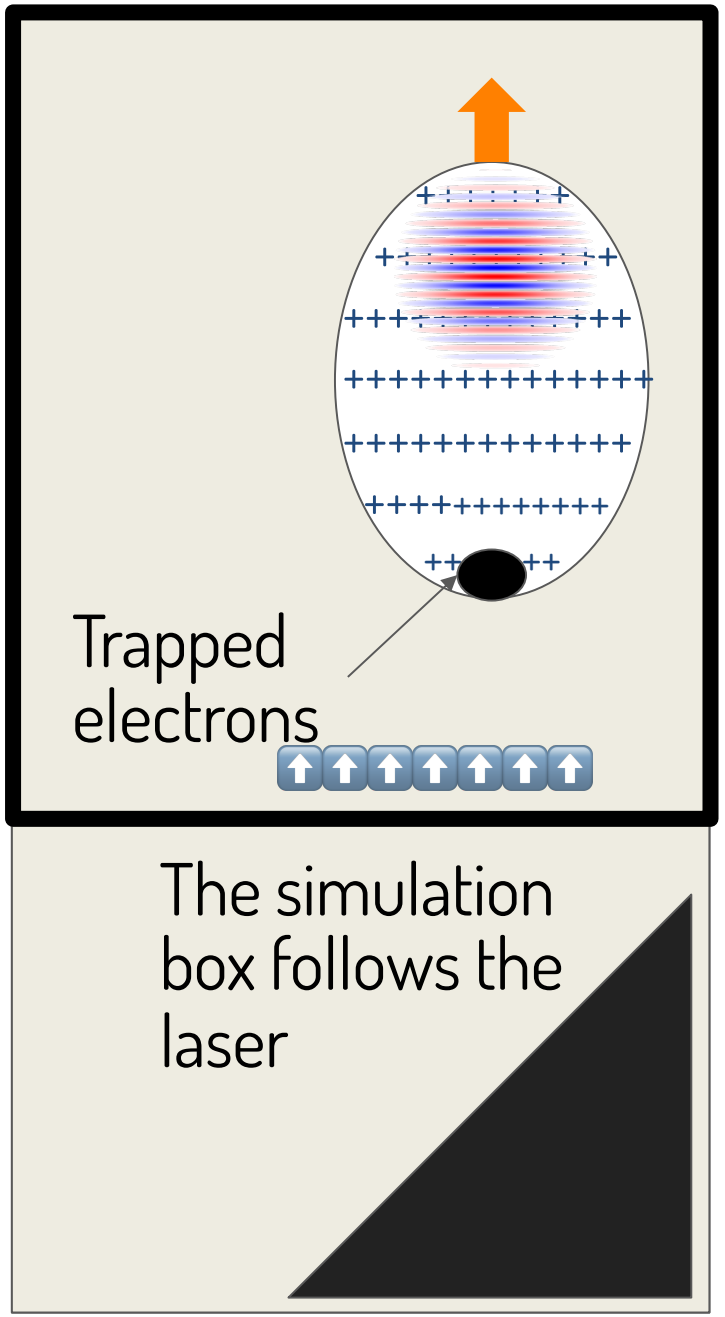
We can have smaller simulation boxes with a “moving window”



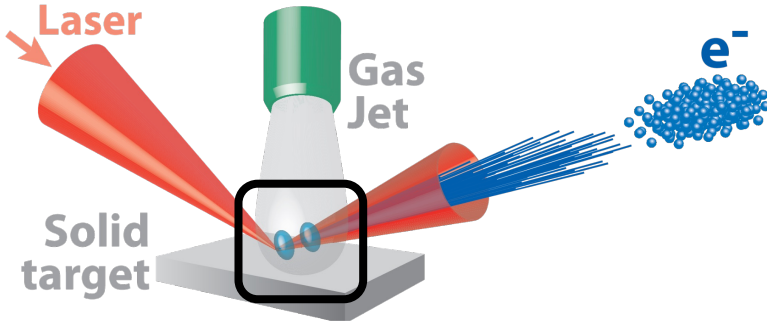
We only need to simulate

~ 100x100x100 μm³ →





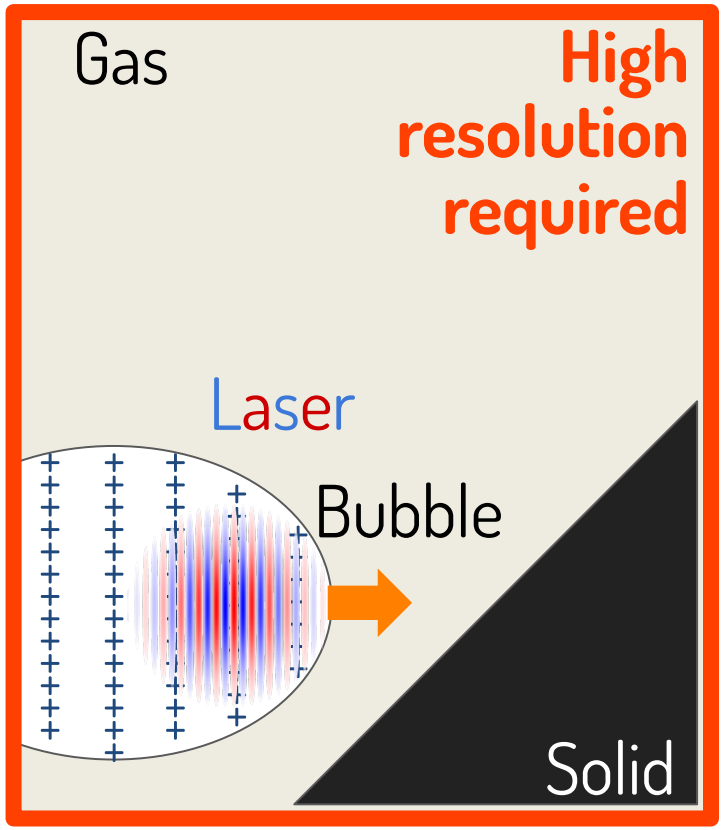
The main challenge concerns laser-solid interaction

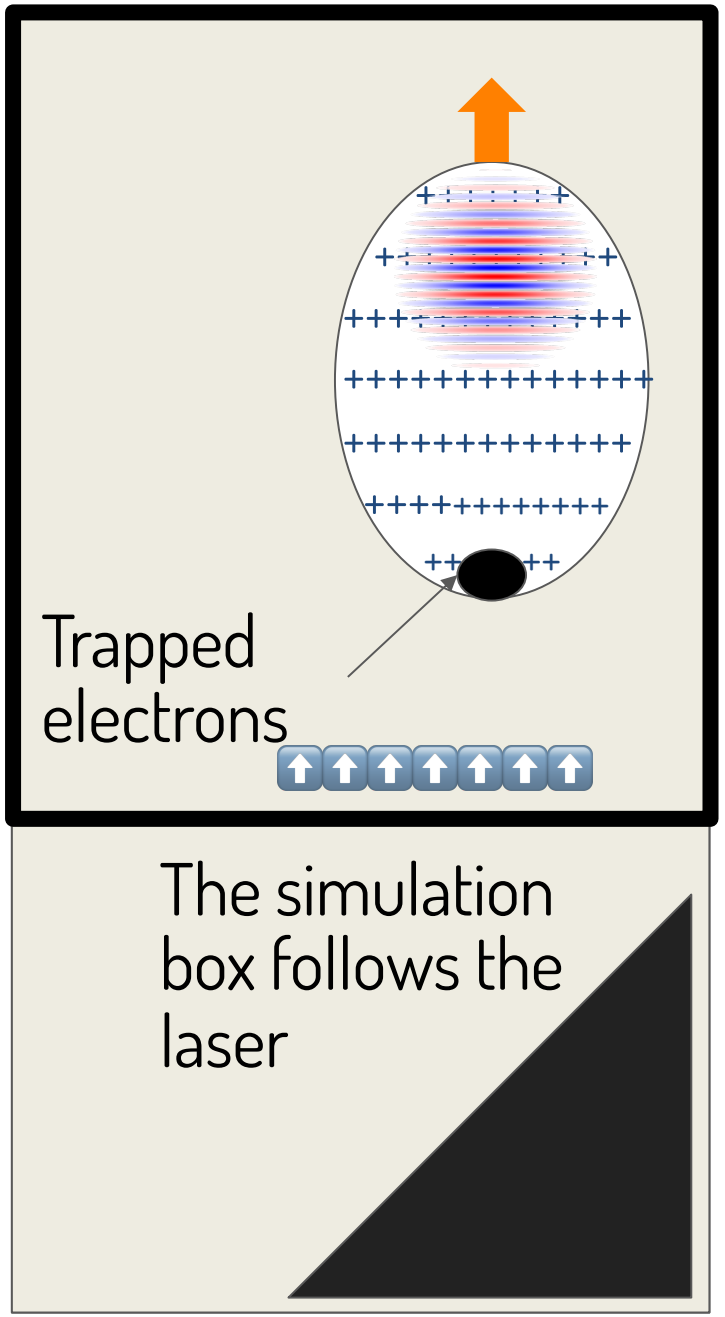


We need a resolution of **few 10s nanometers** for laser-solid interaction →

We only need to simulate

~ 100x100x100 µm³ →





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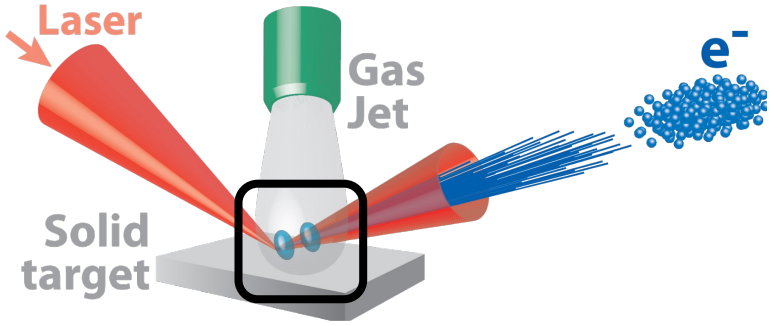


We need a resolution of **few 10s nanometers** for laser-solid interaction →

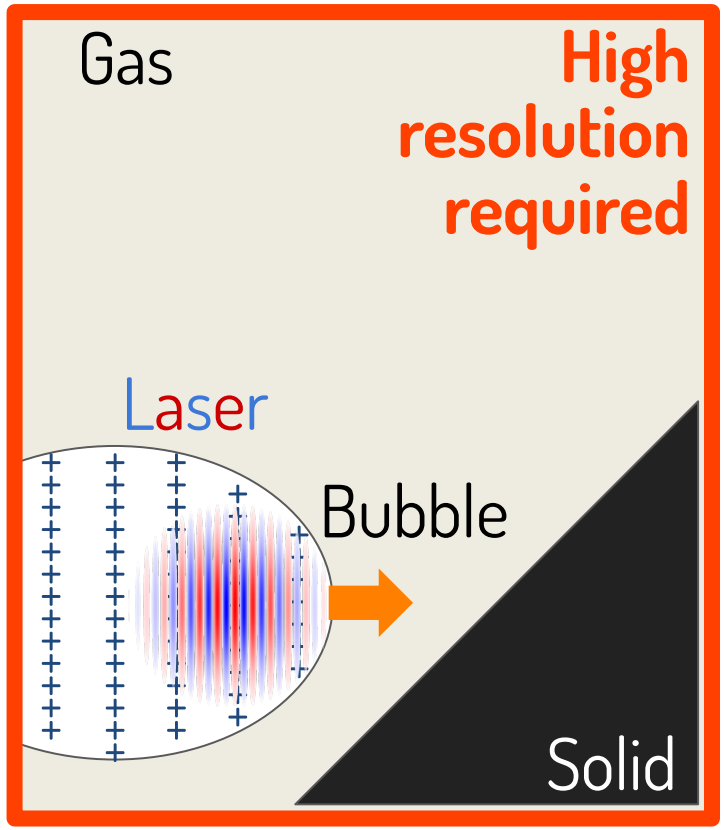
but

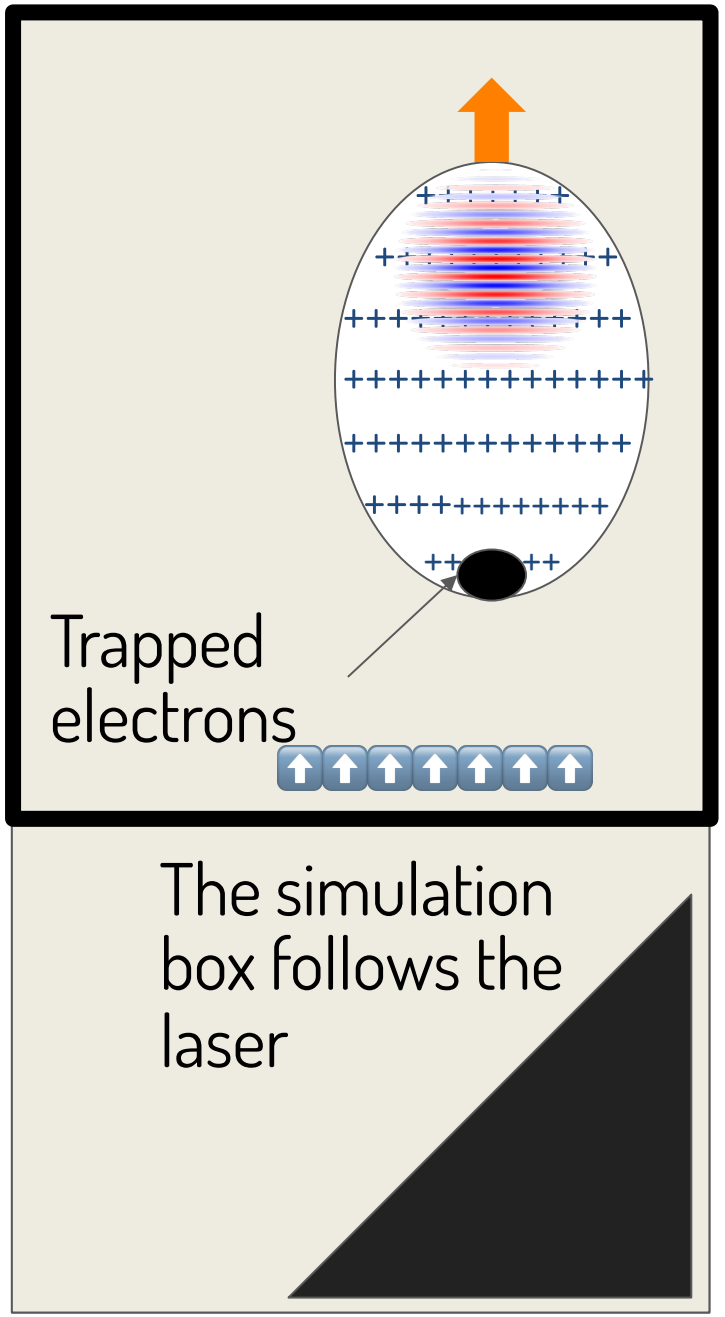
Hefty price to pay:

dt ~ dx and **size ~ (1/dx)³**

We only need to simulate

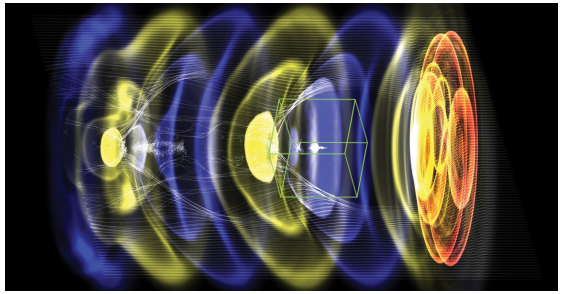
~ 100x100x100 µm³ →





WarpX is an open-source Particle-In-Cell code for the exascale era.

30+ contributors



EXASCALE COMPUTING PROJECT

BERKELEY LAB

DE LA RECHERCHE À L'INDUSTRIE

Lawrence Livermore National Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

DESY.

CERN

MODERN ELECTRON

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Documentation: **ecp-warpx.github.io/**

mac OS

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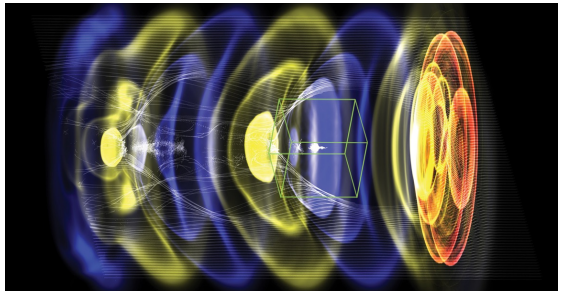

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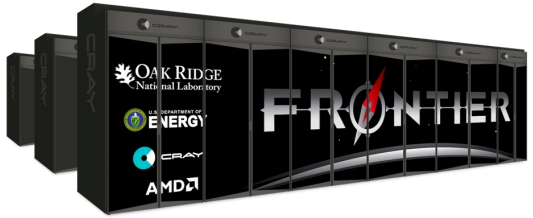
Gordon Bell prize winner @

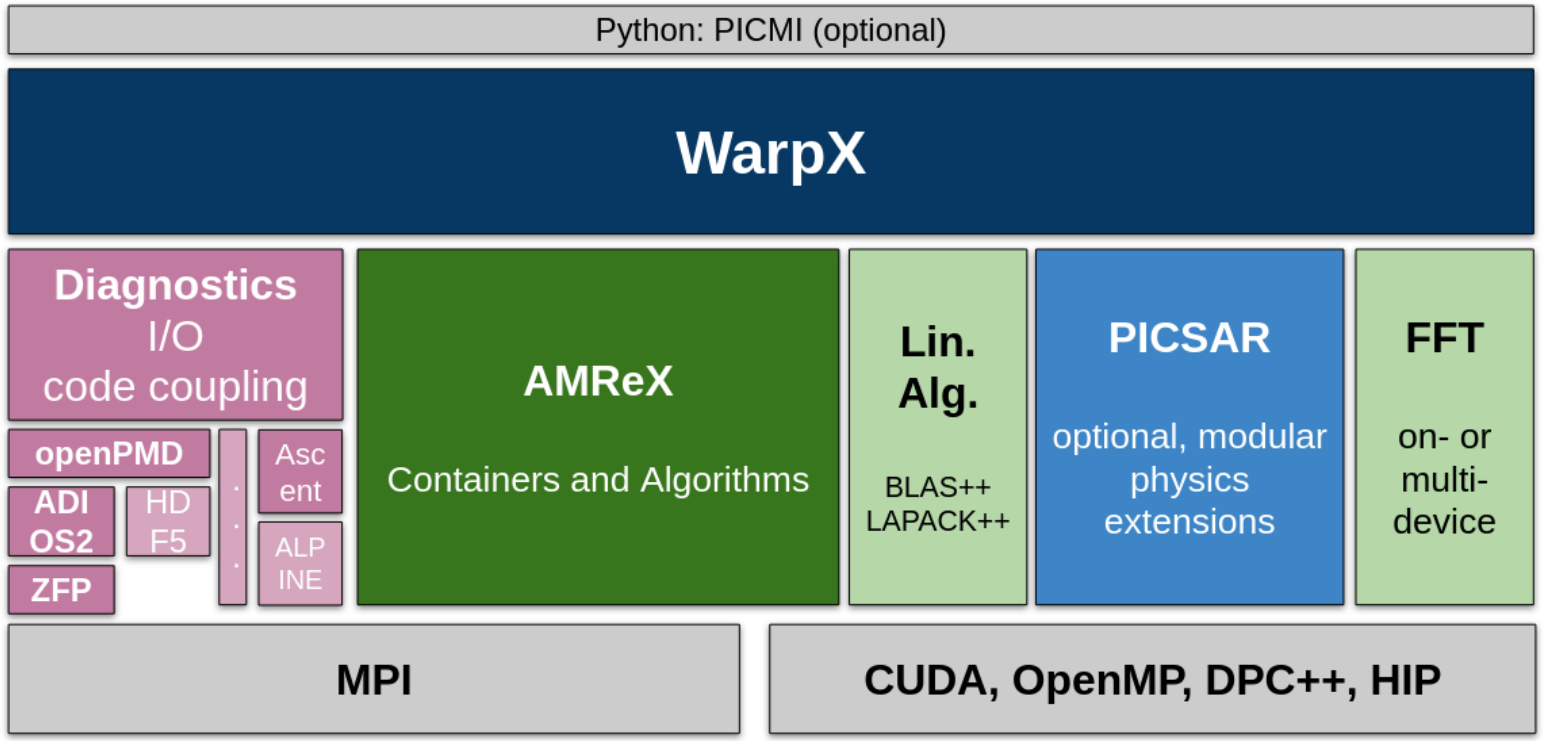
SC22

From your laptop to the largest supercomputers in the world!

We need the most powerful supercomputers

		Architecture	Rank in TOP500
	Perlmutter	Nvidia A100	11
	Summit	Nvidia V100	7
	Frontier	AMD MI250X	1
	Fugaku	Fujitsu A64FX	4

WarpX is built on top of the AMReX library, which provides performance portability



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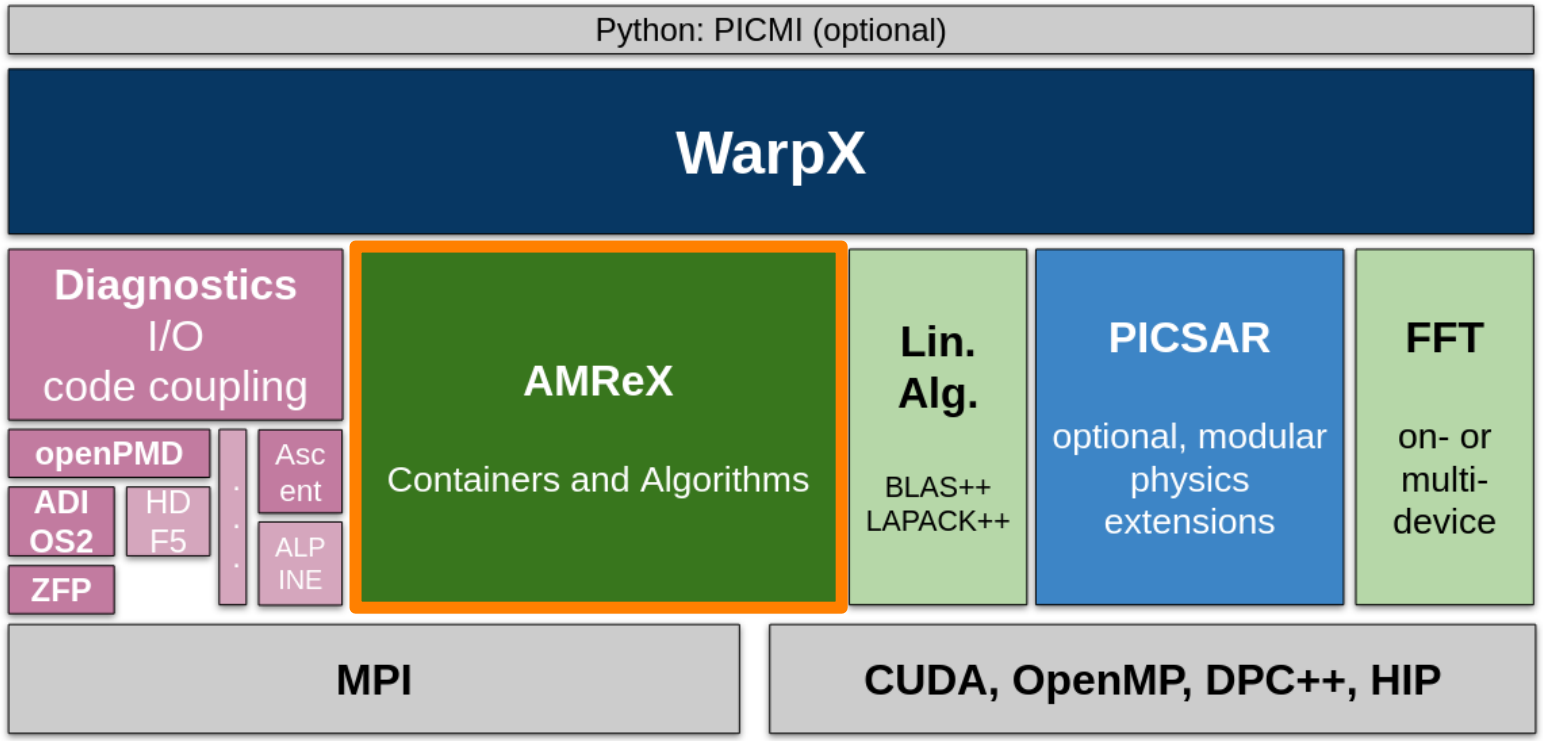

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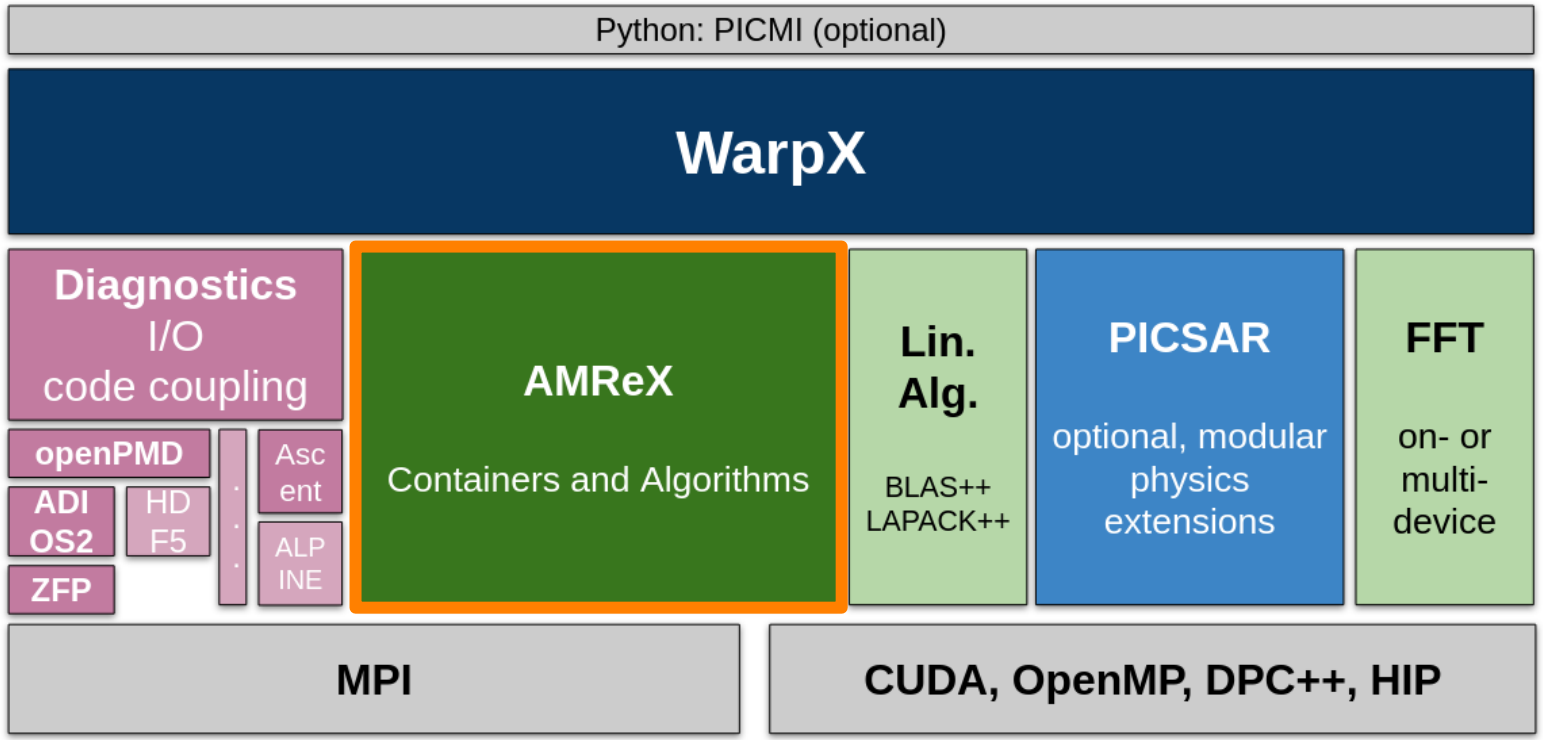
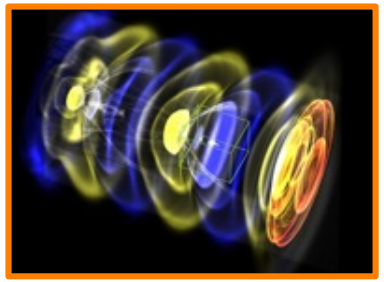


Single source approach

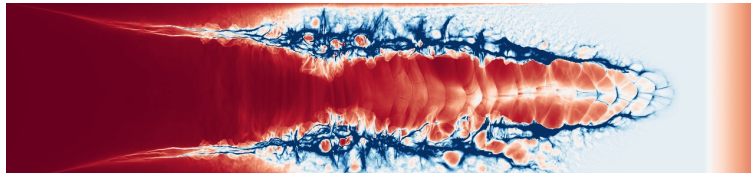
```cpp
using namespace amrex;

int N = 1'000'000;

Gpu::ManagedVector<double> a(N);
Gpu::ManagedVector<double> b(N);
Gpu::ManagedVector<double> c(N);
Gpu::ManagedVector<double> result(N);

/* OTHER CODE*/

auto d_a = a.data();
auto d_b = b.data();
auto d_c = c.data();
auto d_result = c.data();

ParallelFor(N,
    [=] AMREX_GPU_DEVICE (int i){
        d_result[i] = d_a[i]*d_b[i] + d_c[i];
    });
```

WarpX can be used for many different applications

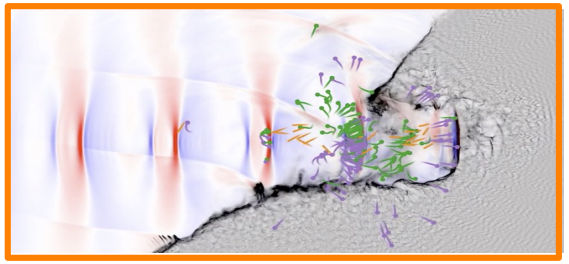


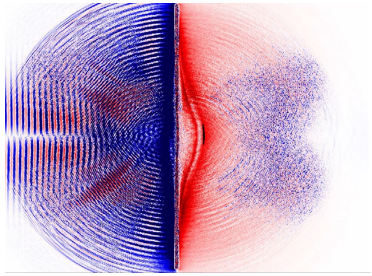
Plasma accelerators (LBNL, DESY, SLAC)

Laser-ion acceleration – advanced mechanisms (LBNL)



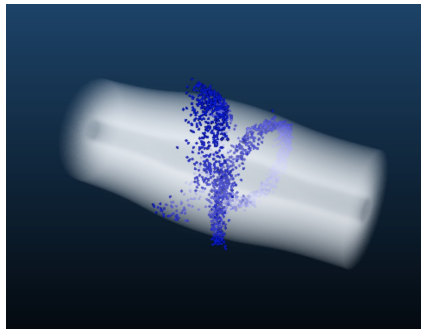
Plasma mirrors and high-field physics + QED (CEA Saclay/LBNL)



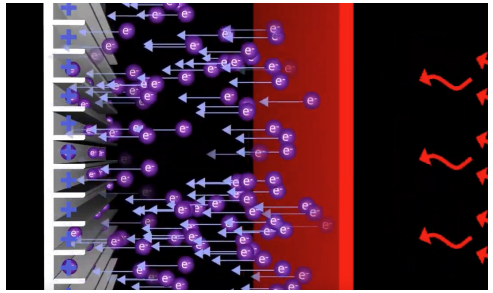


Laser-ion acceleration – laser pulse shaping (LLNL)

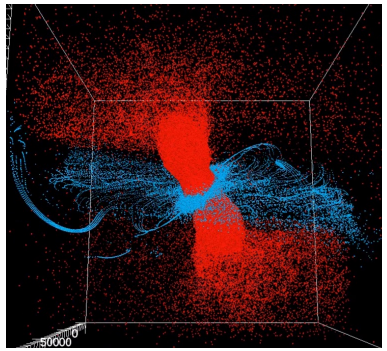
Fusion devices (Zap Energy, Avalanche Energy)



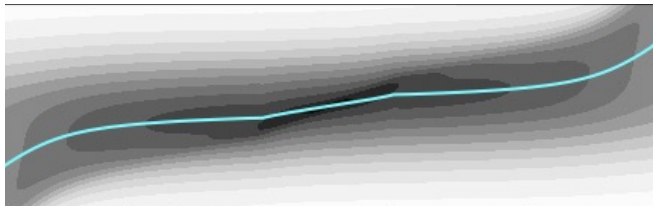
Thermionic converter (Modern Electron)



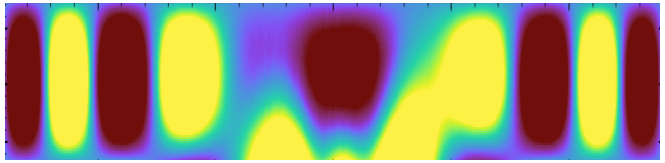
Pulsars, magnetic reconnection (LBNL)

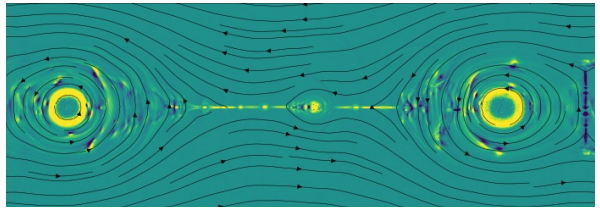


Magnetic fusion sheaths (LLNL)



Microelectronics (LBNL) – ARTEMIS





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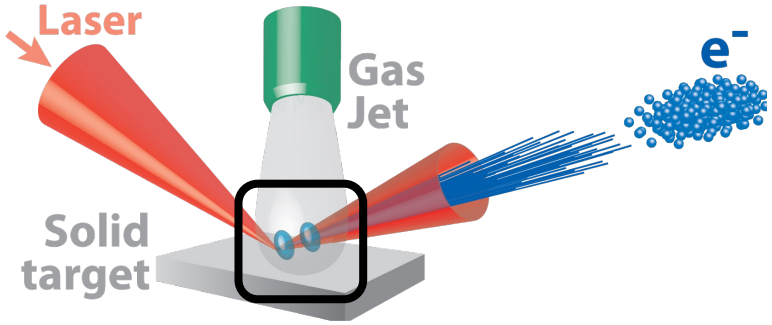
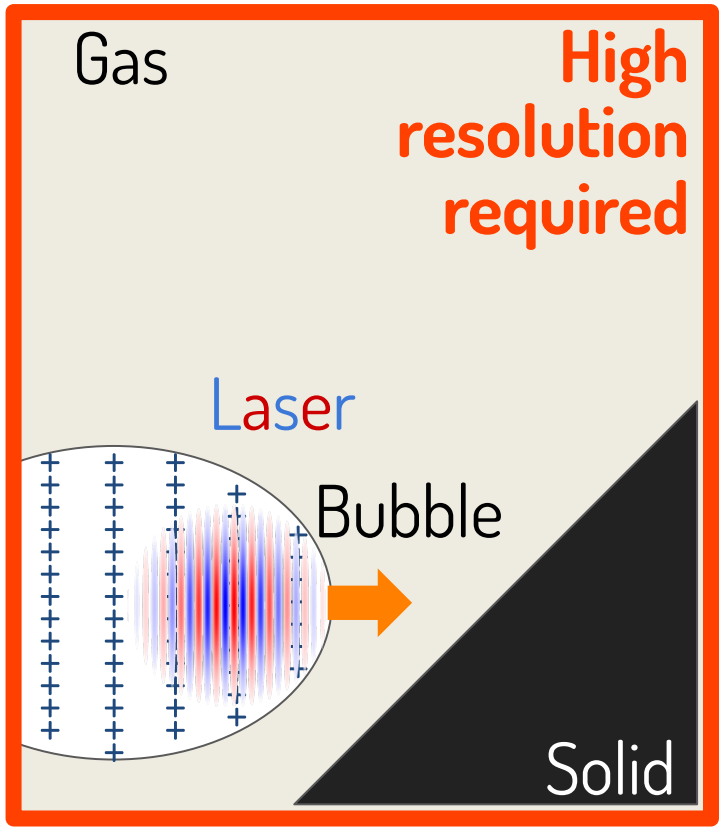
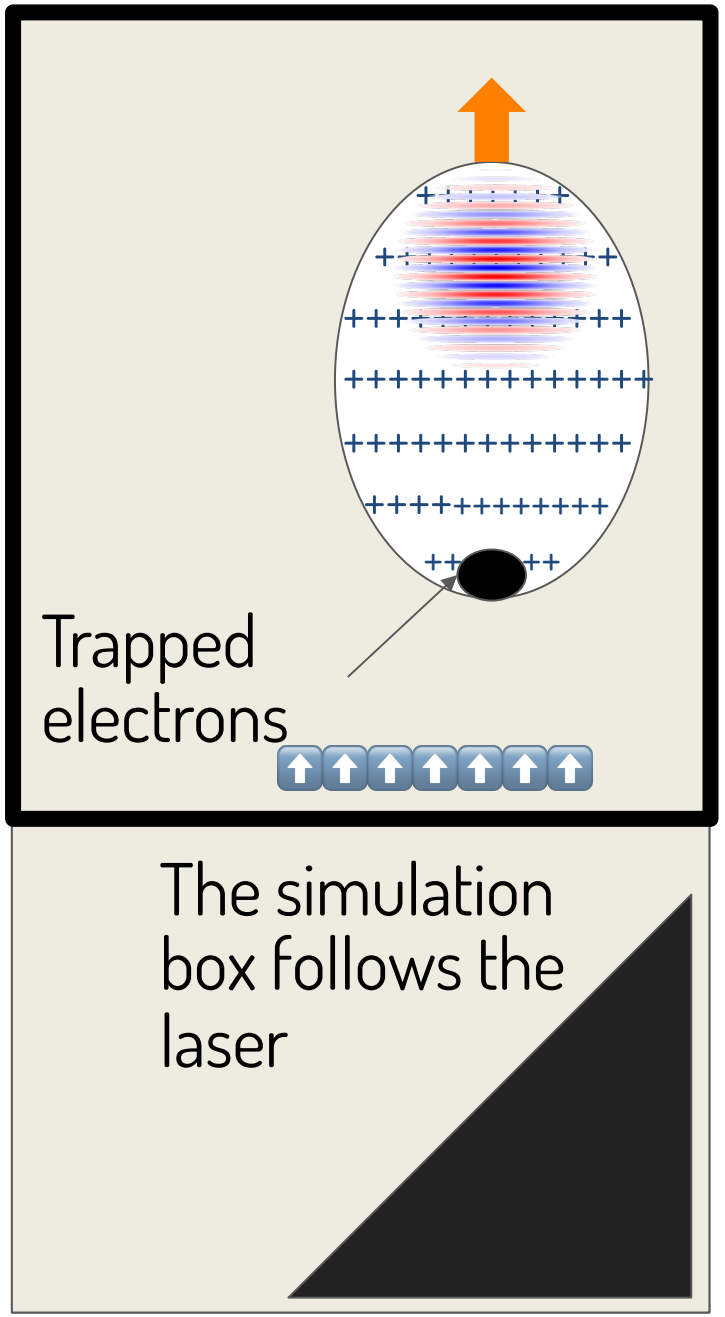


We need to simulate

on mm/cm→





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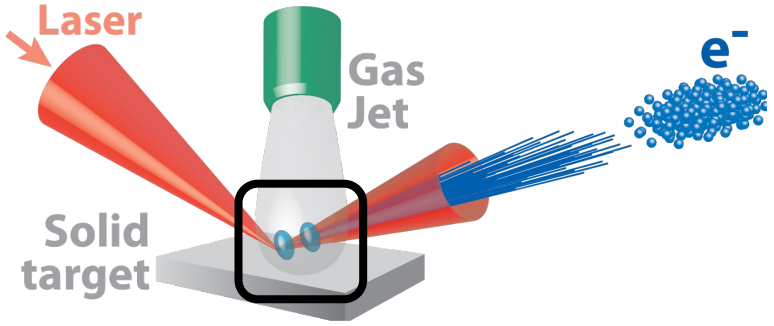

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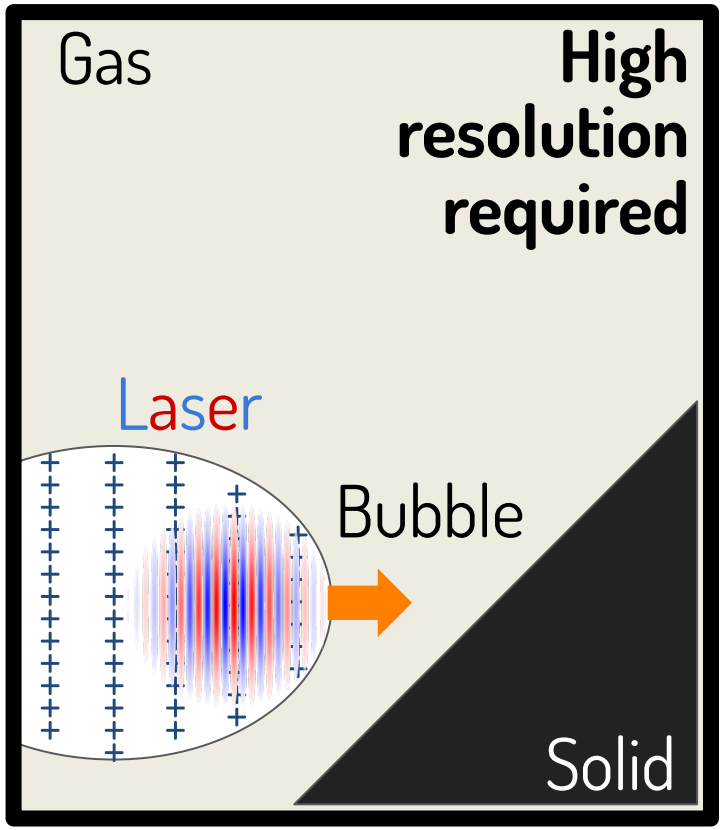

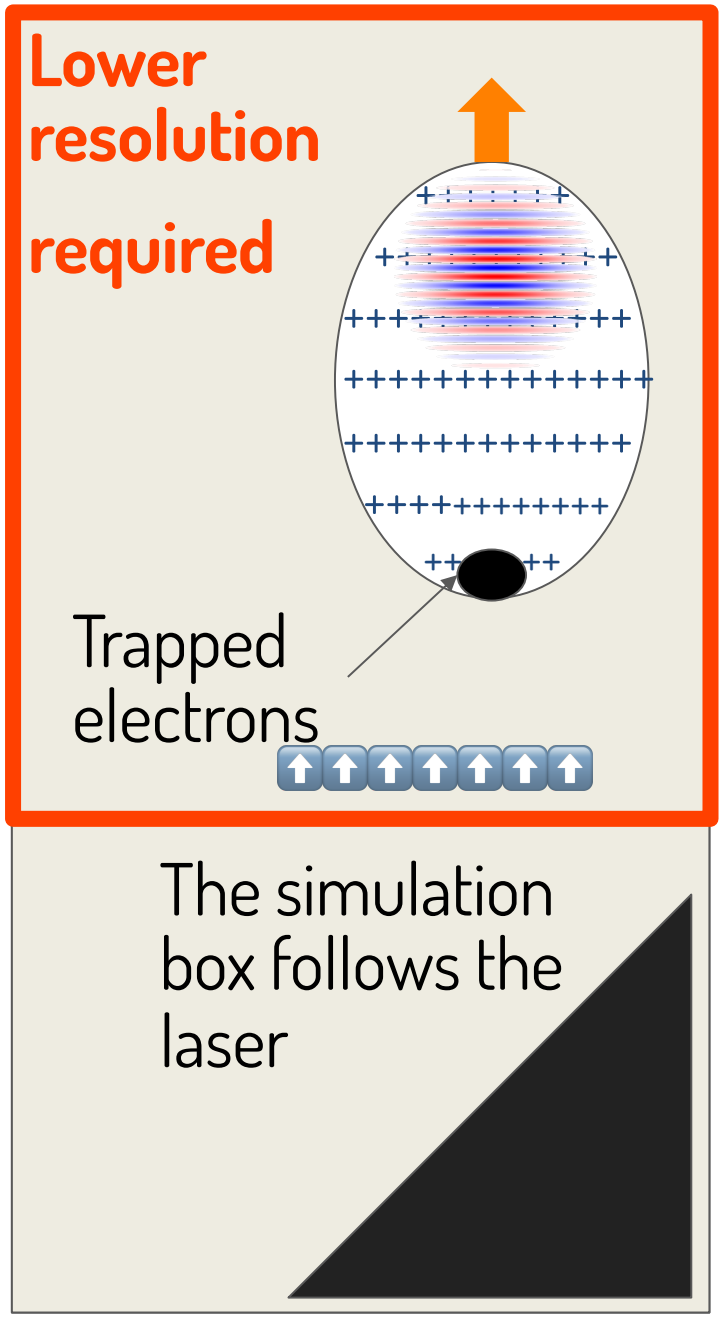

How do we switch resolution in the middle of the simulation?

Mesh refinement, one of the most advanced WarpX features, comes to help

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Mesh refinement in a Particle-In-Cell code is **a nightmare!**

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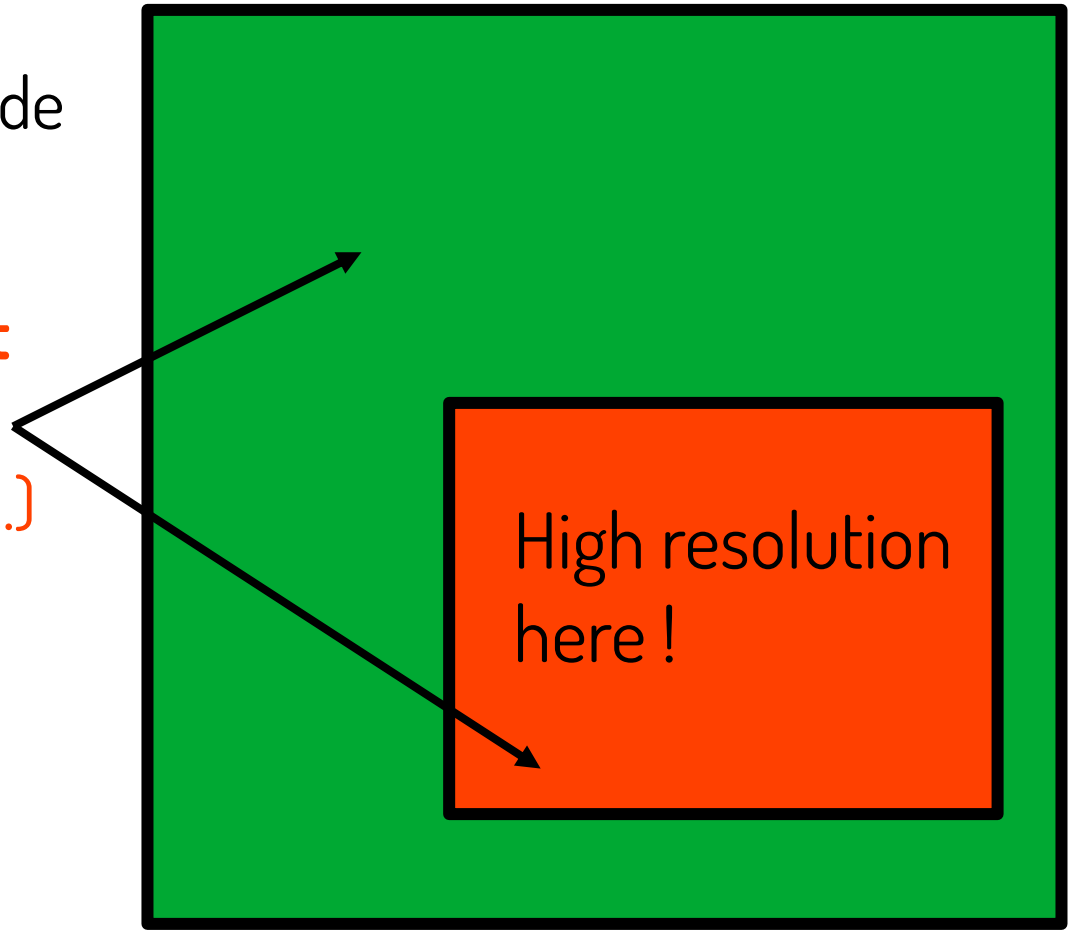
Electromagnetic waves have different dispersion relations in the two areas!
(spurious reflections, unphysical effects…)



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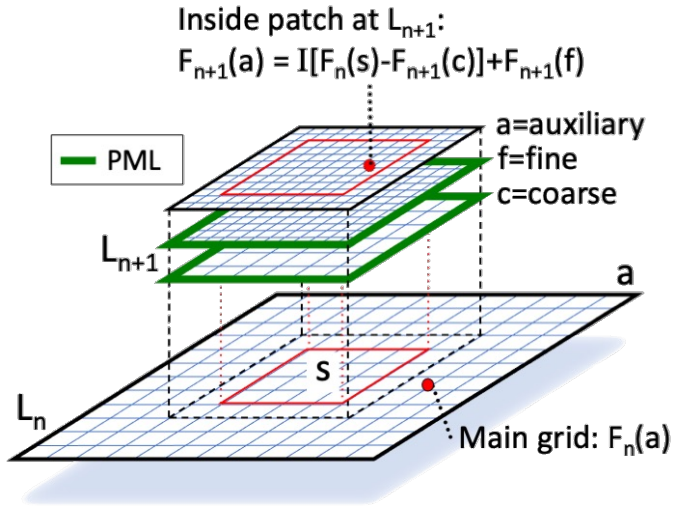
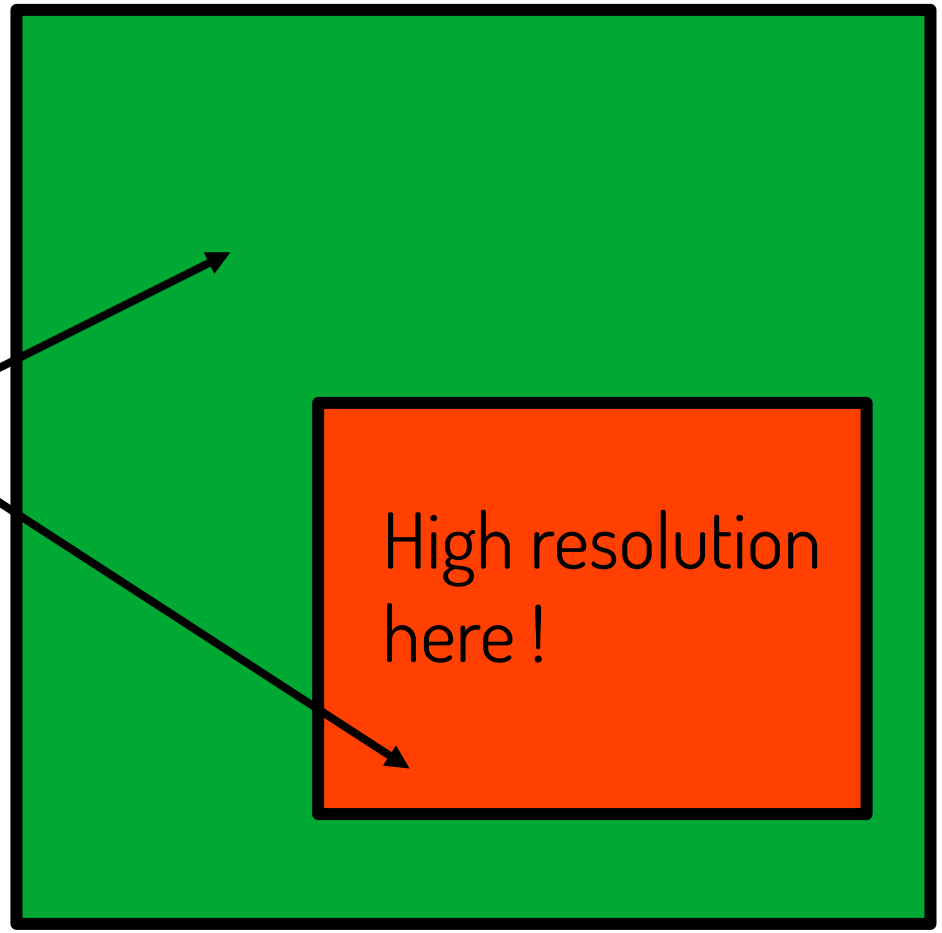
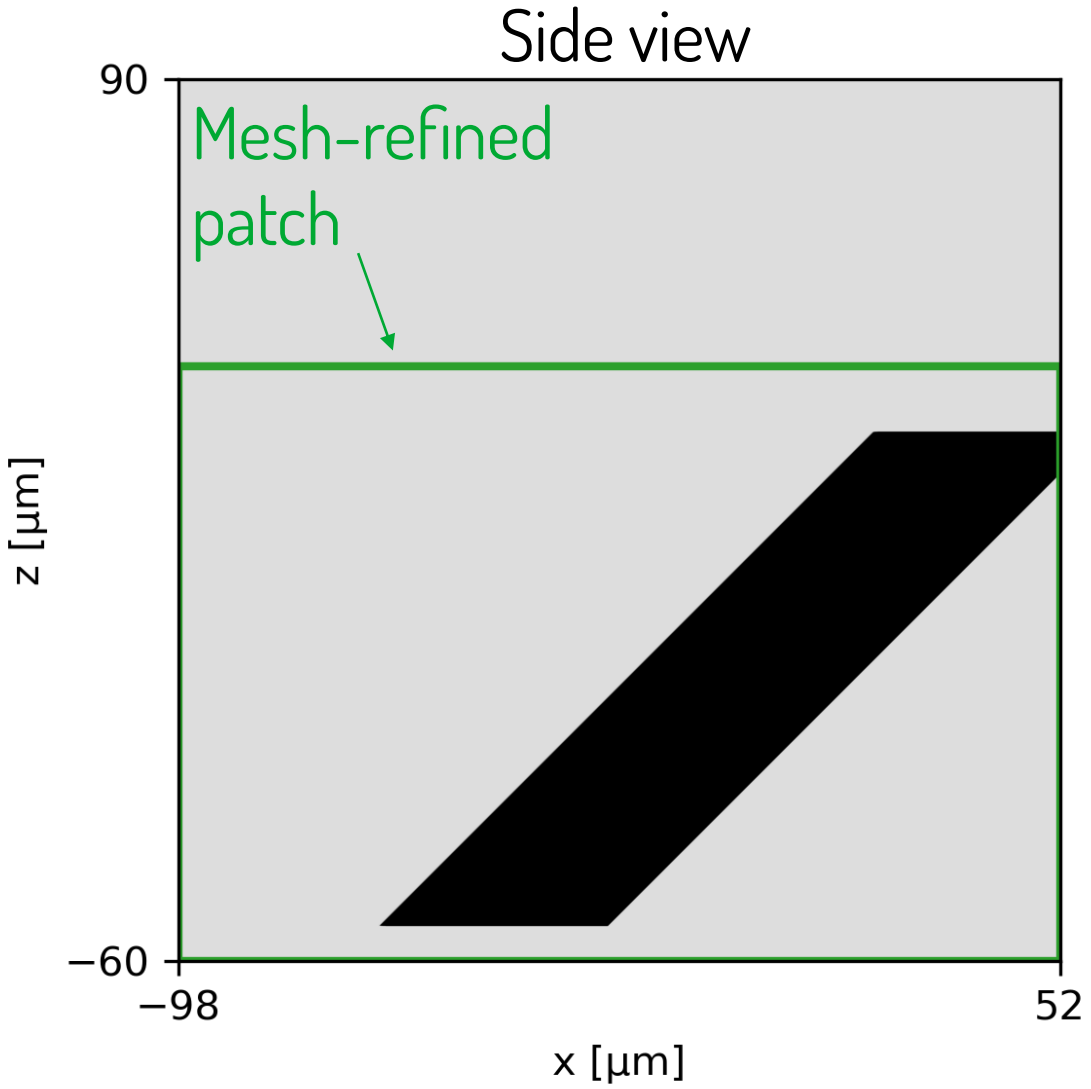
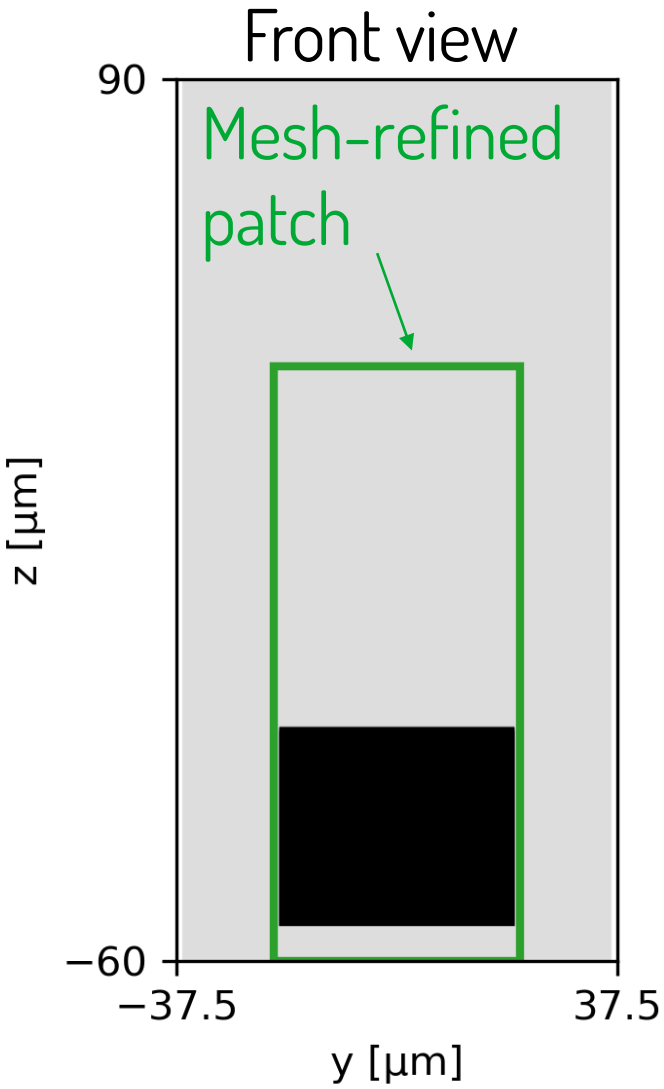




J.-L. Vay et al, Phys. Plasmas 11, 2928 (2004)
R. Lehe et al, Phys. Rev. E 106, 045306 (2022)

2D slices of our 3D simulations highlight the acceleration process





← 3D simulation on 4096 Summit nodes

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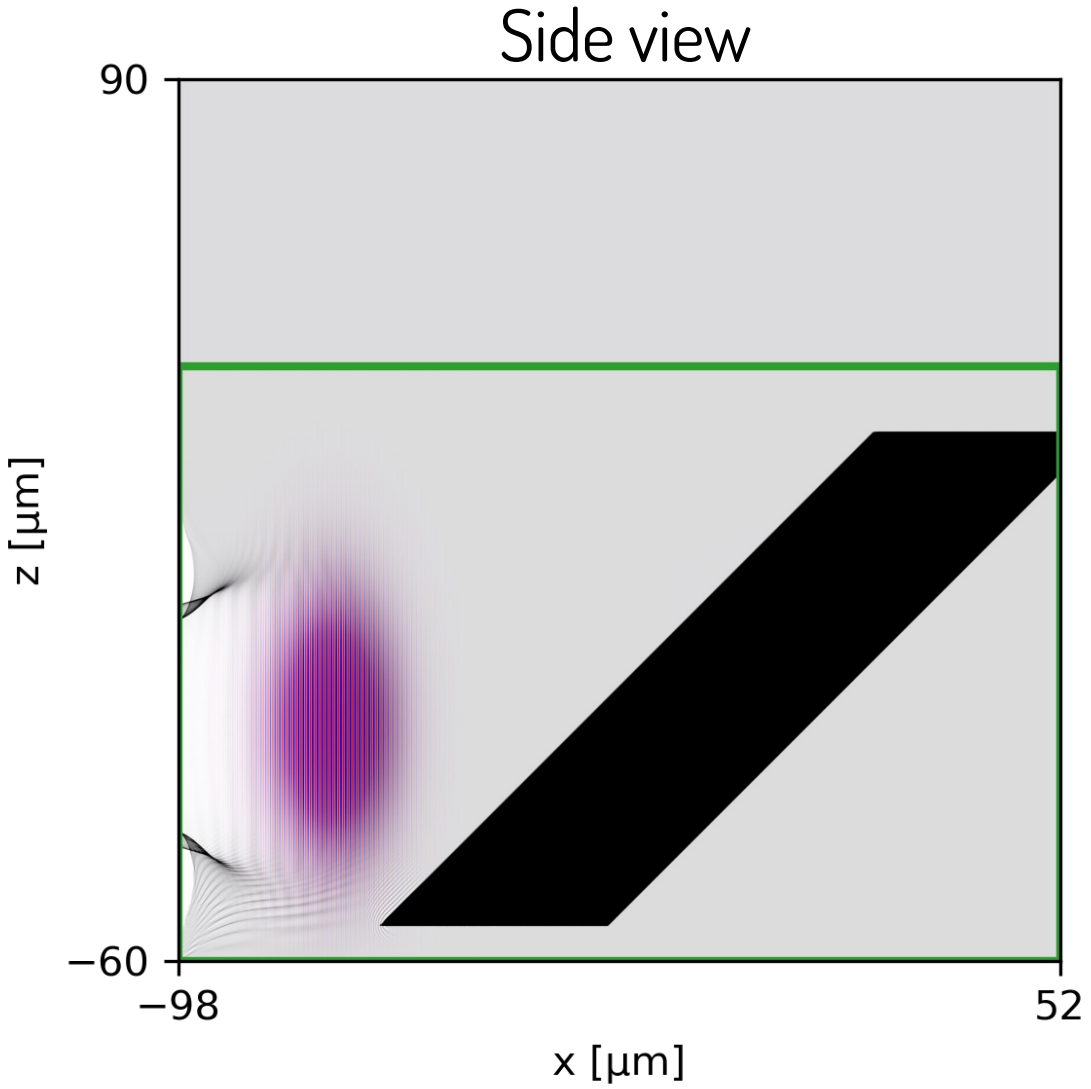

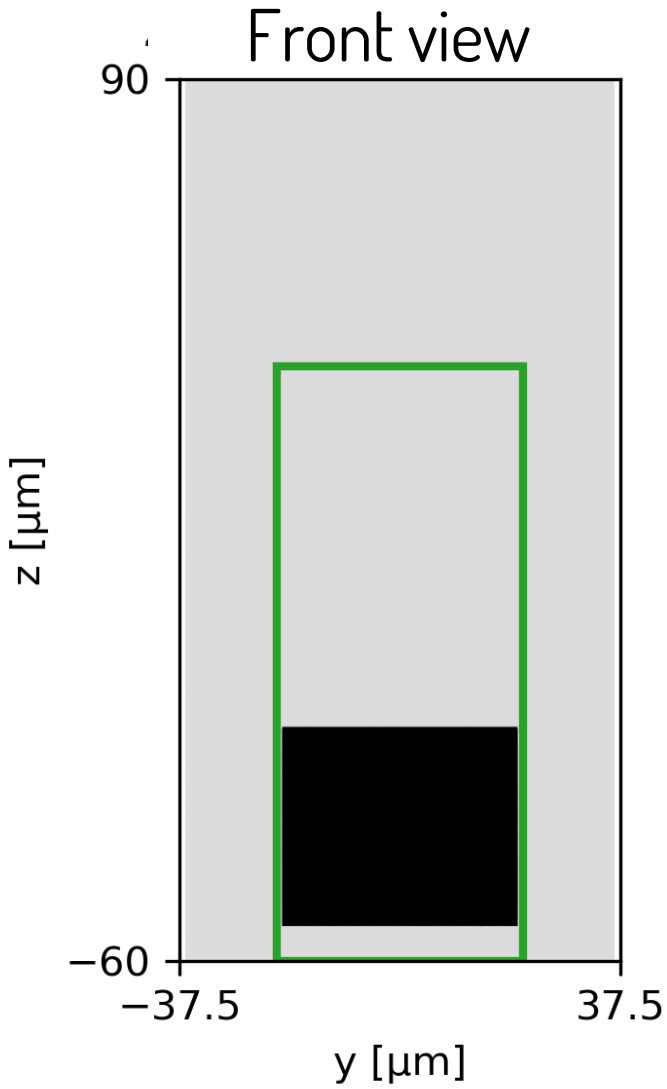

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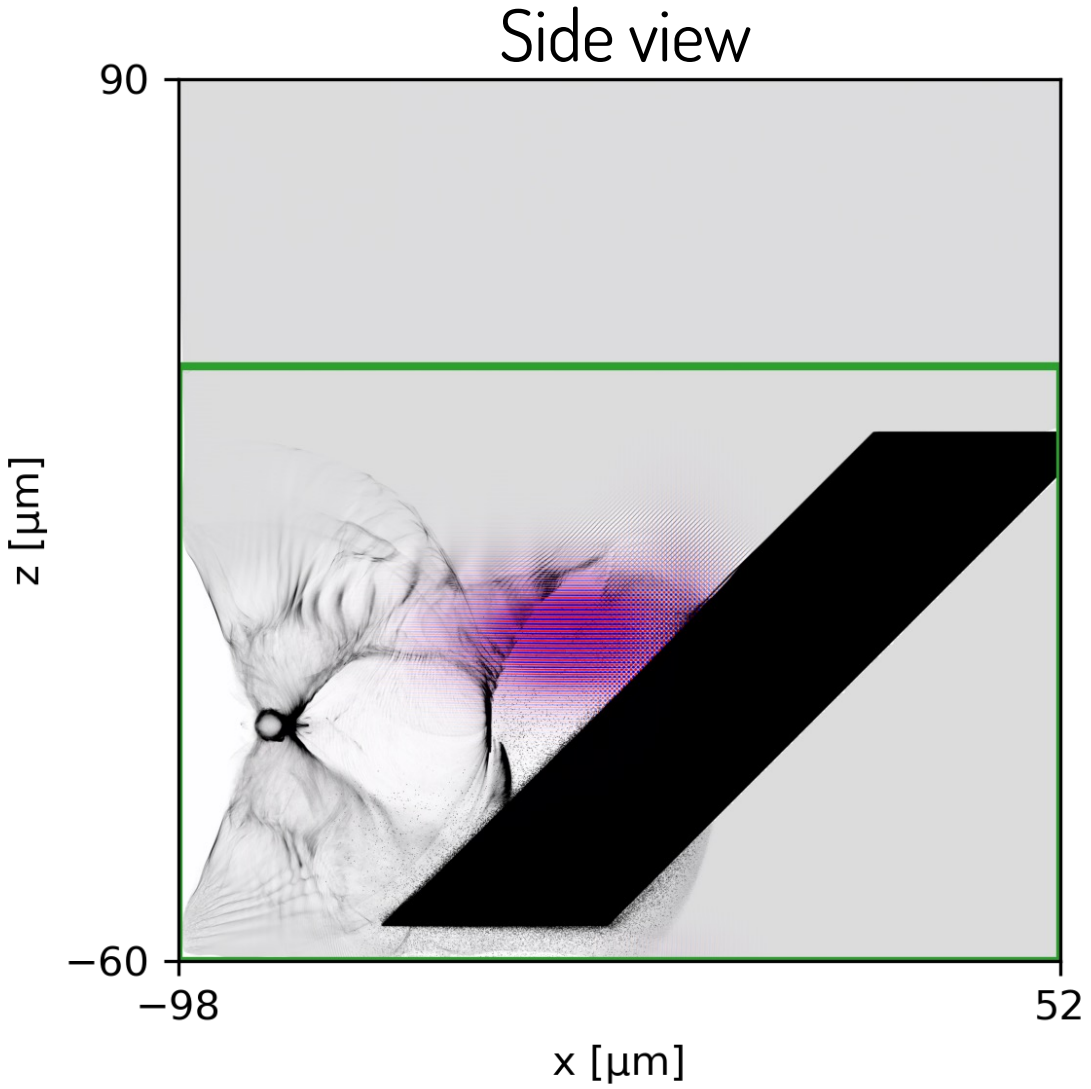
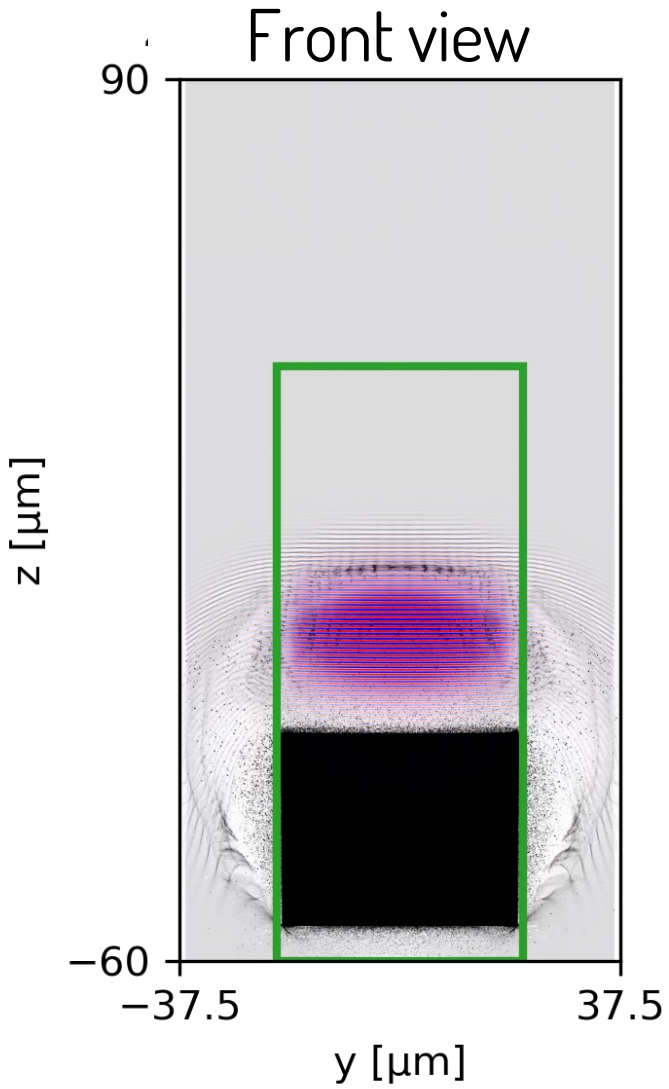
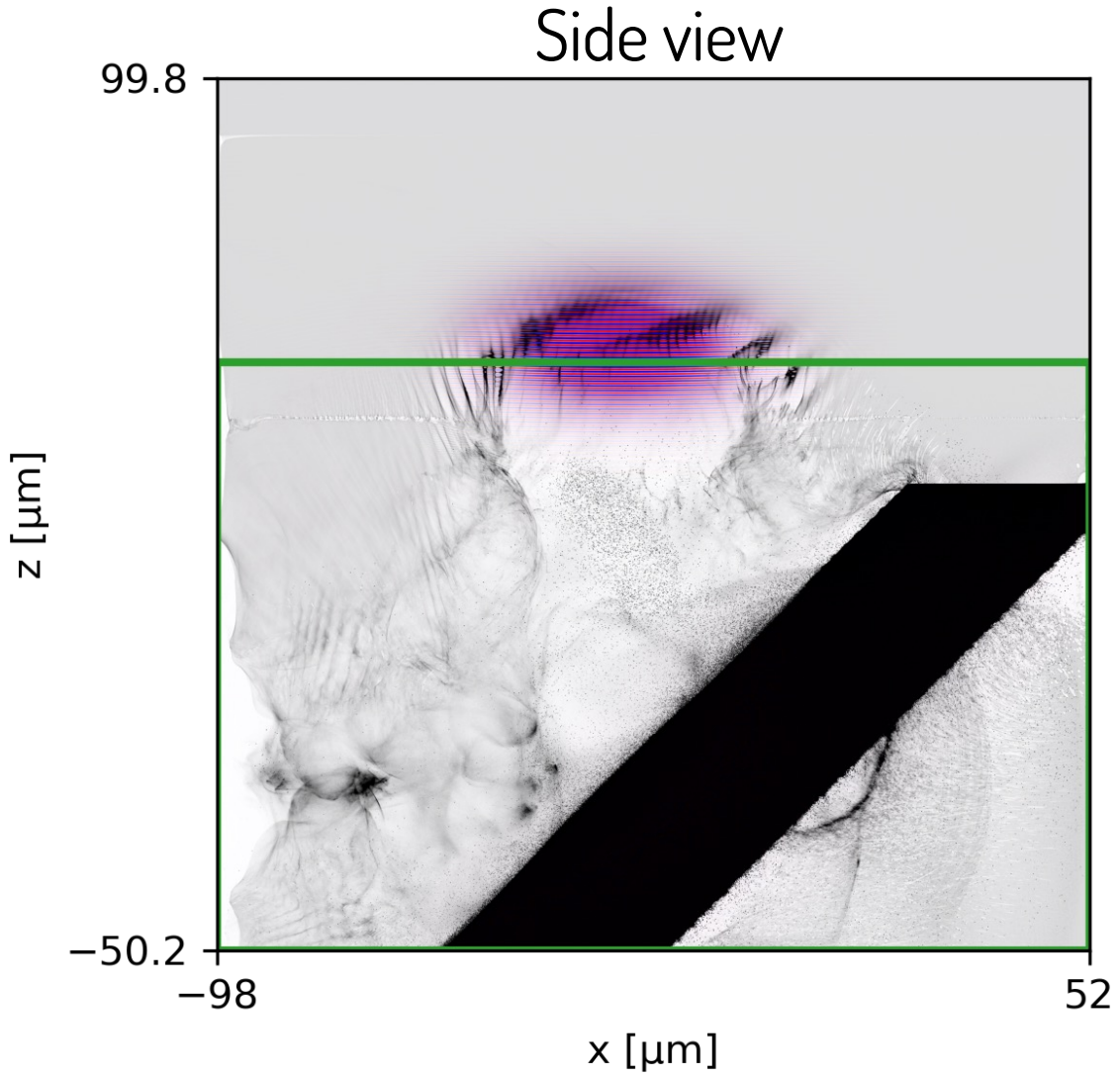
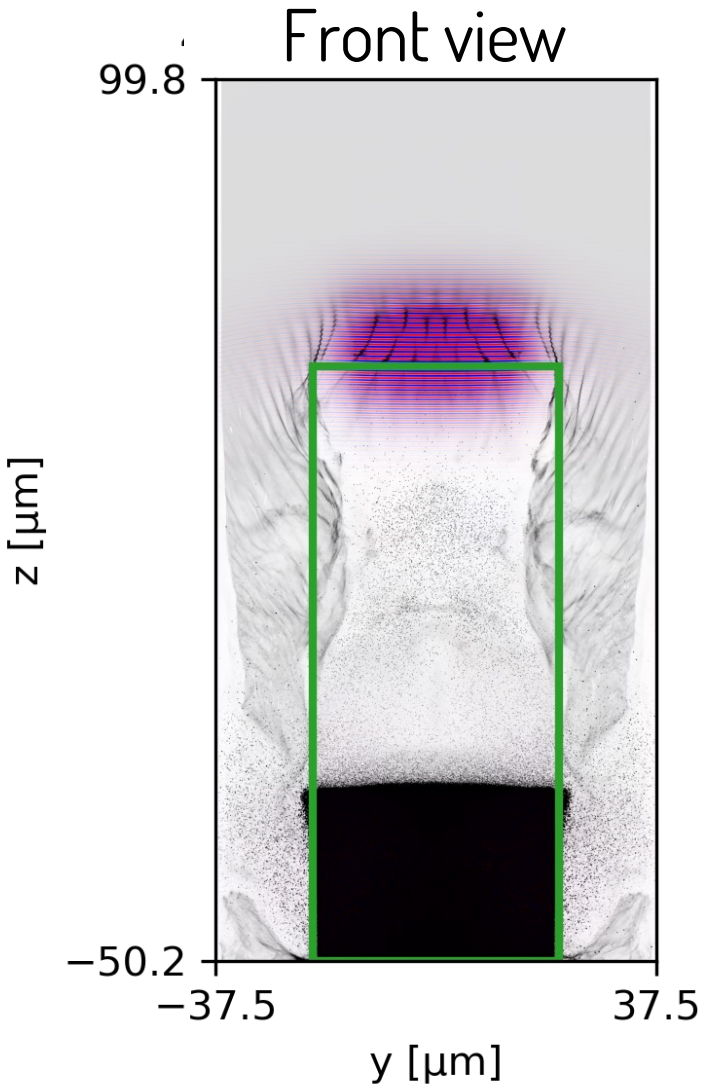




← 3D simulation on 4096 Summit nodes

2D slices of our 3D simulations highlight the acceleration process





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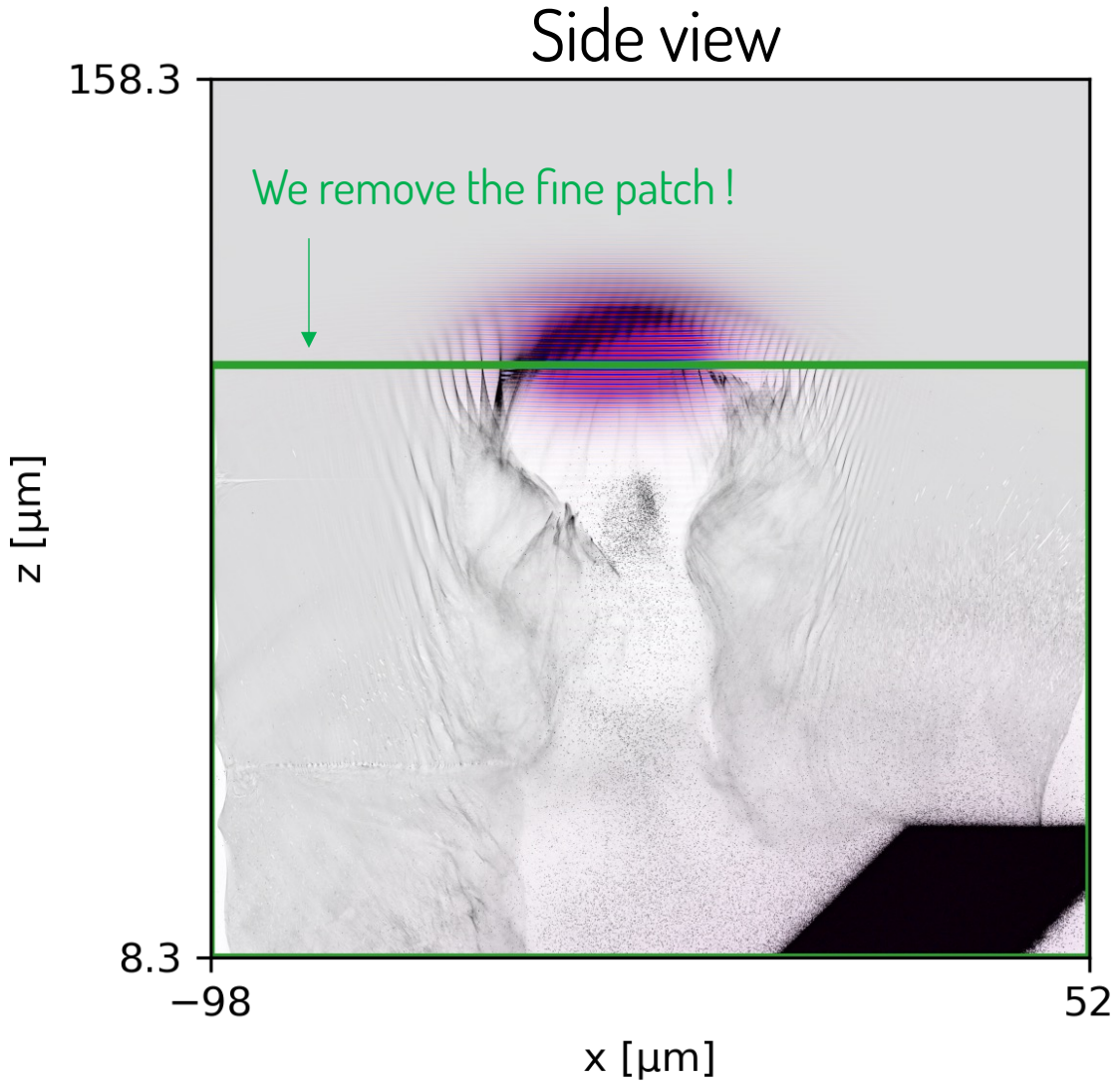

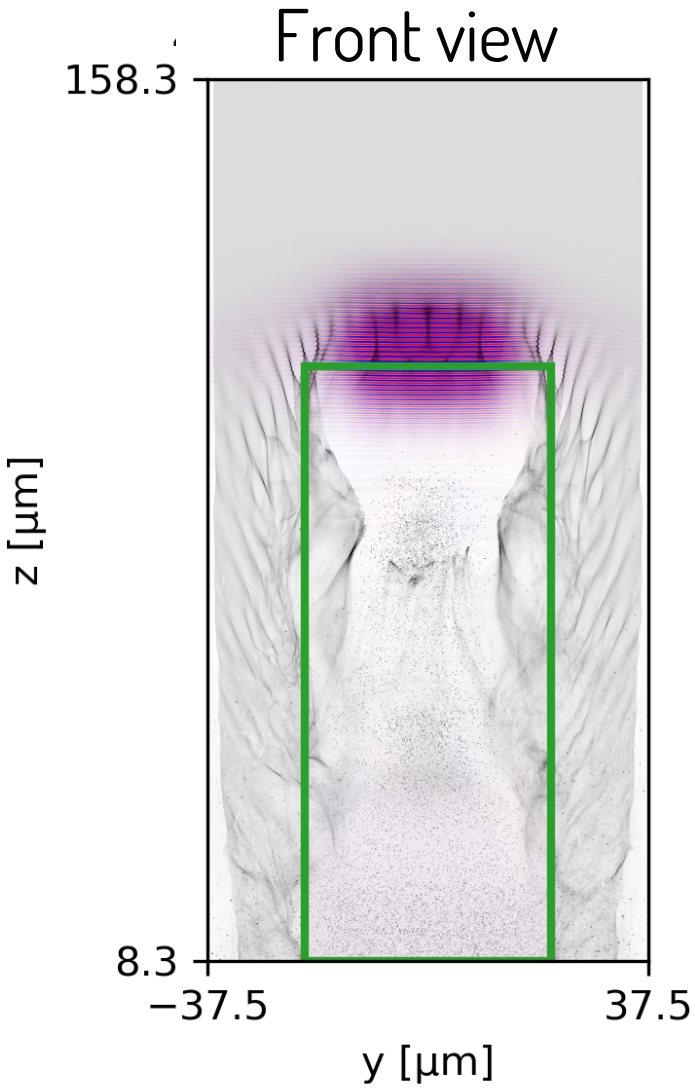

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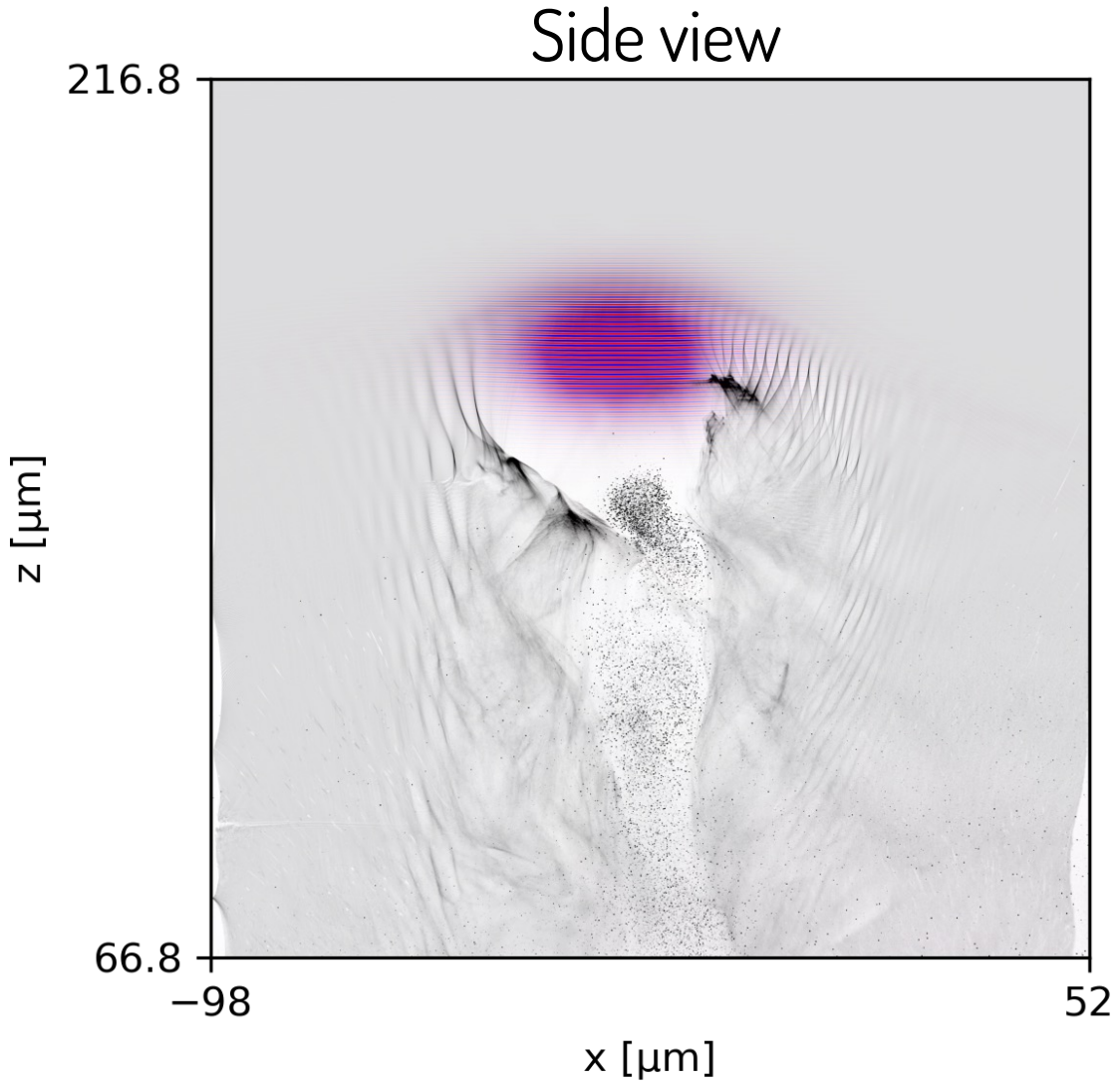

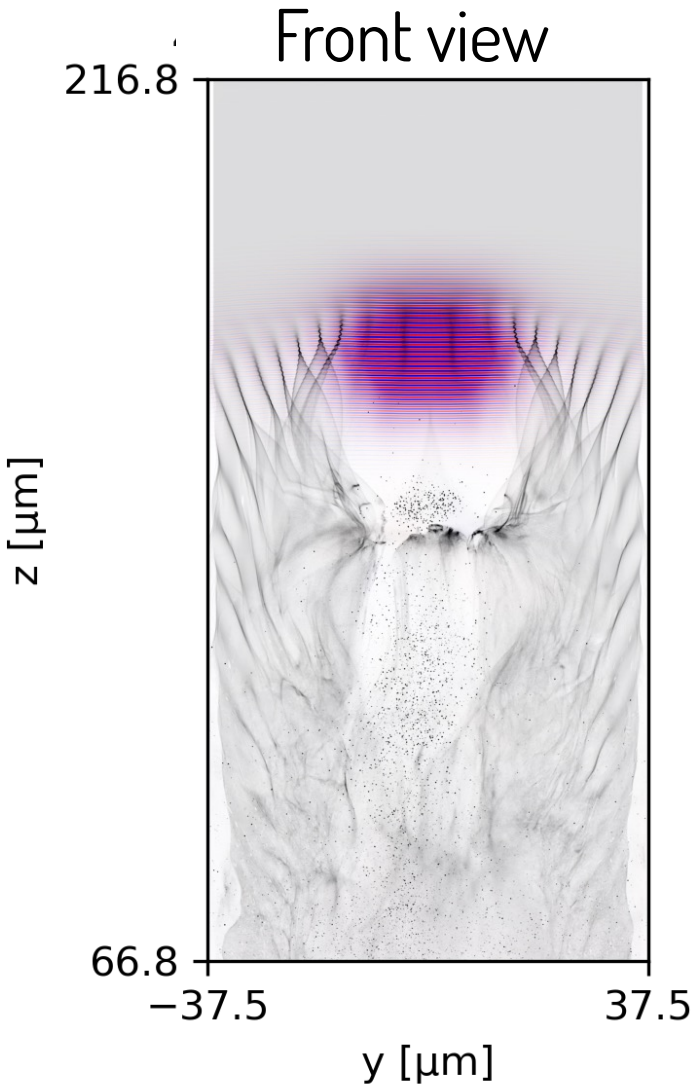

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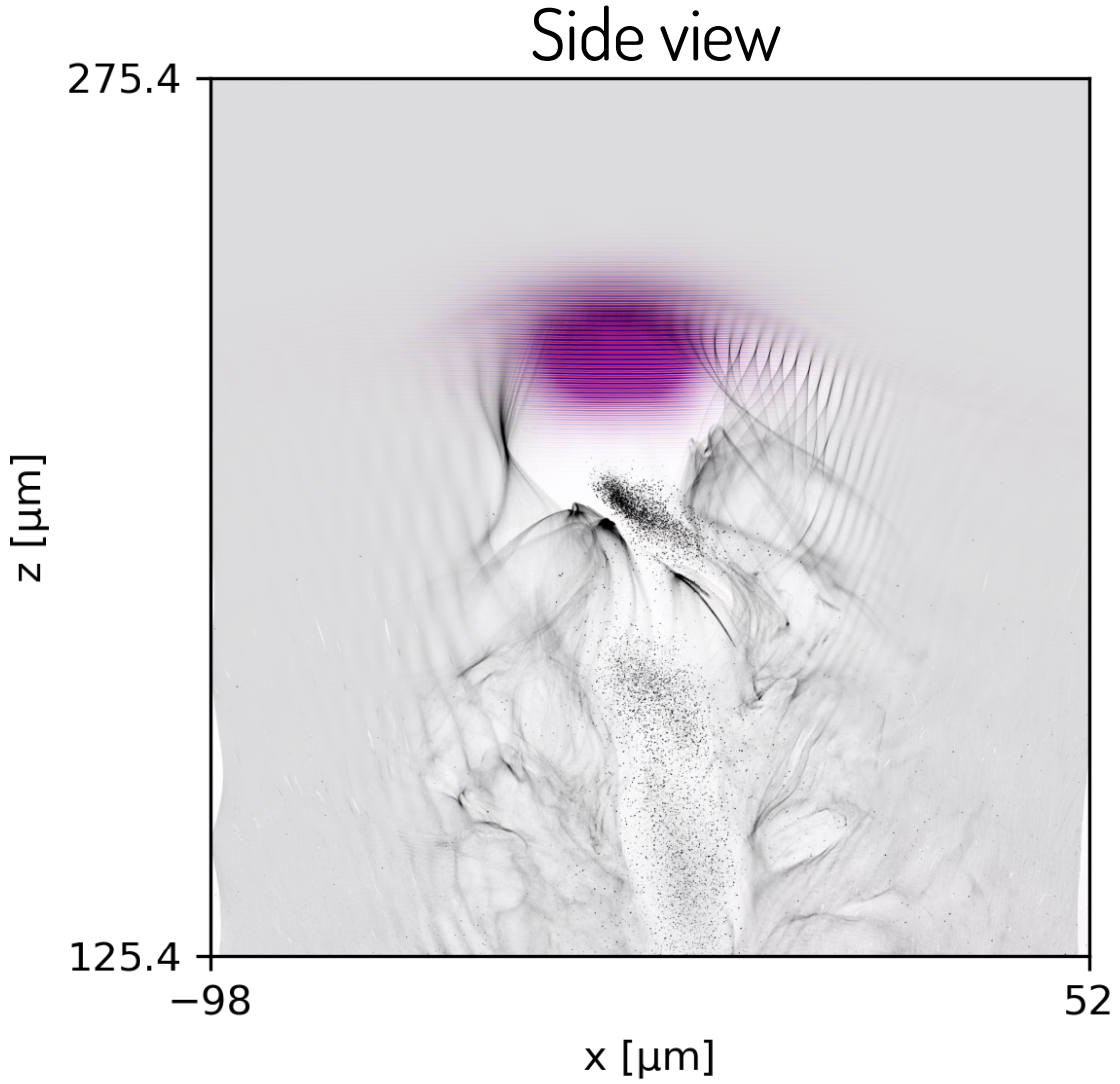

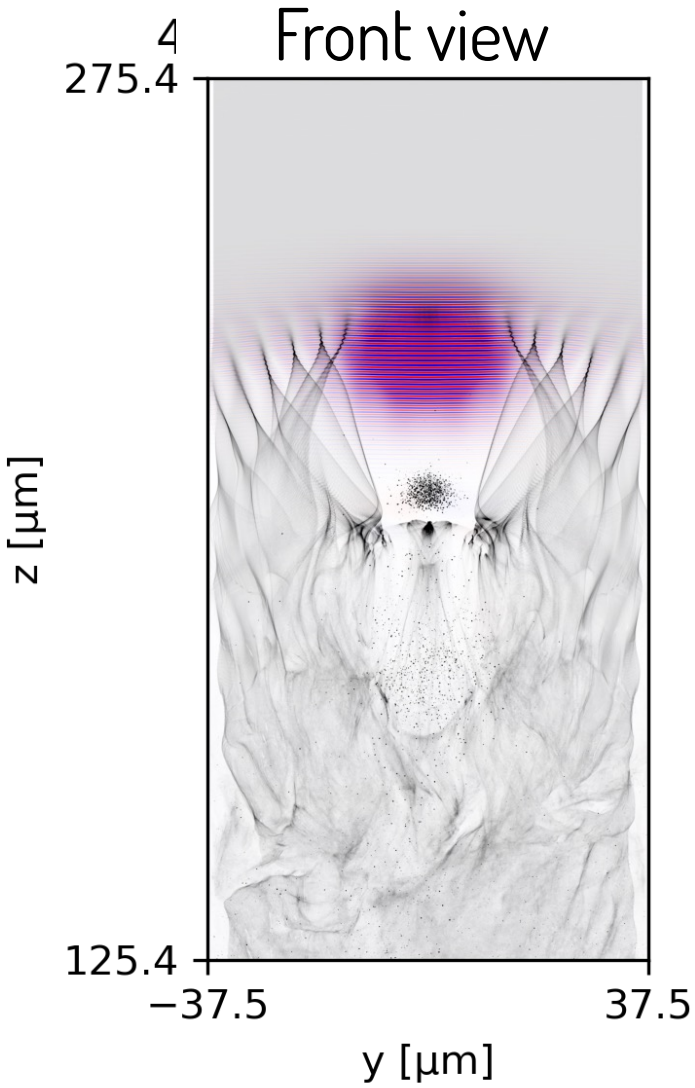

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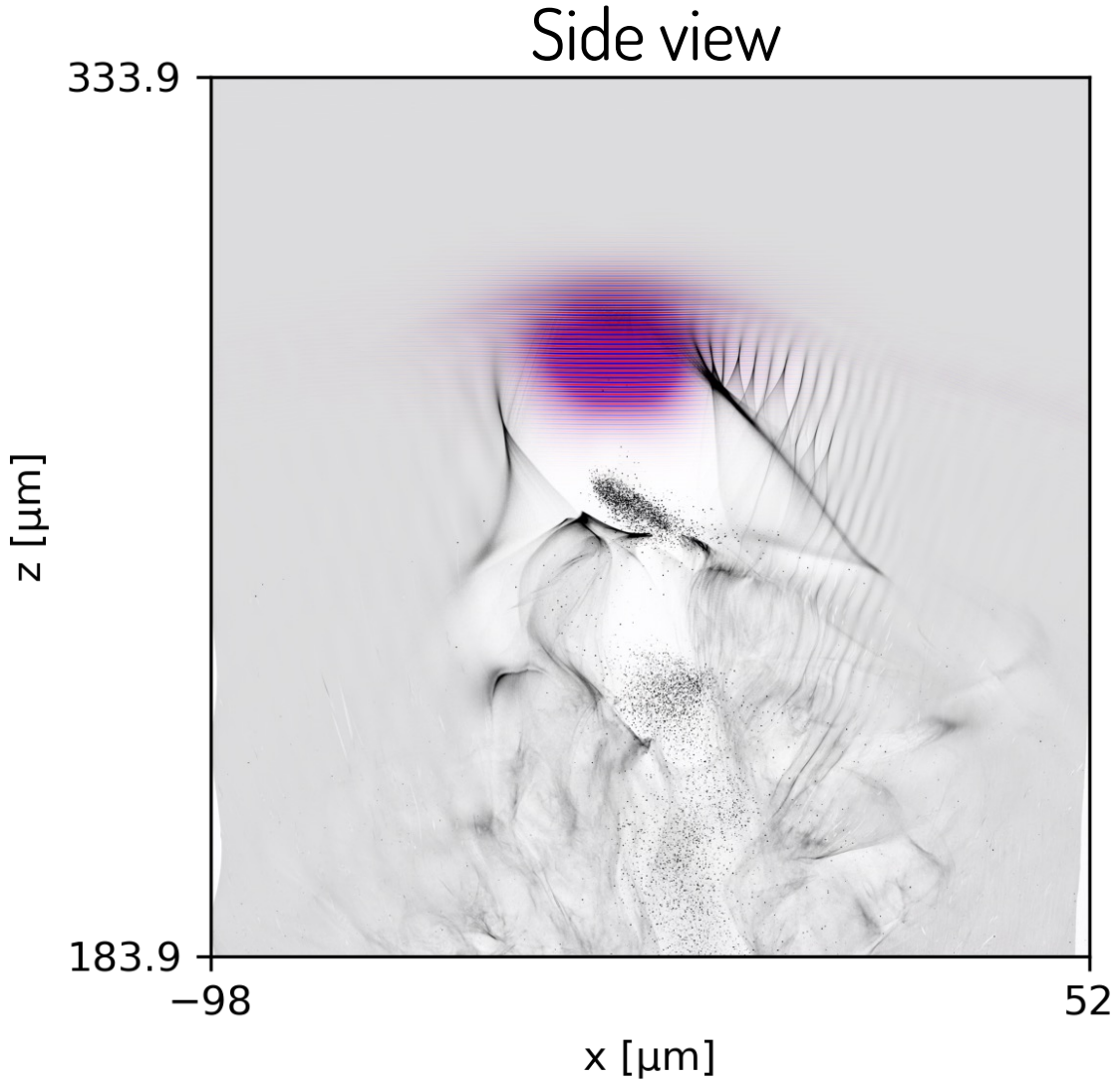

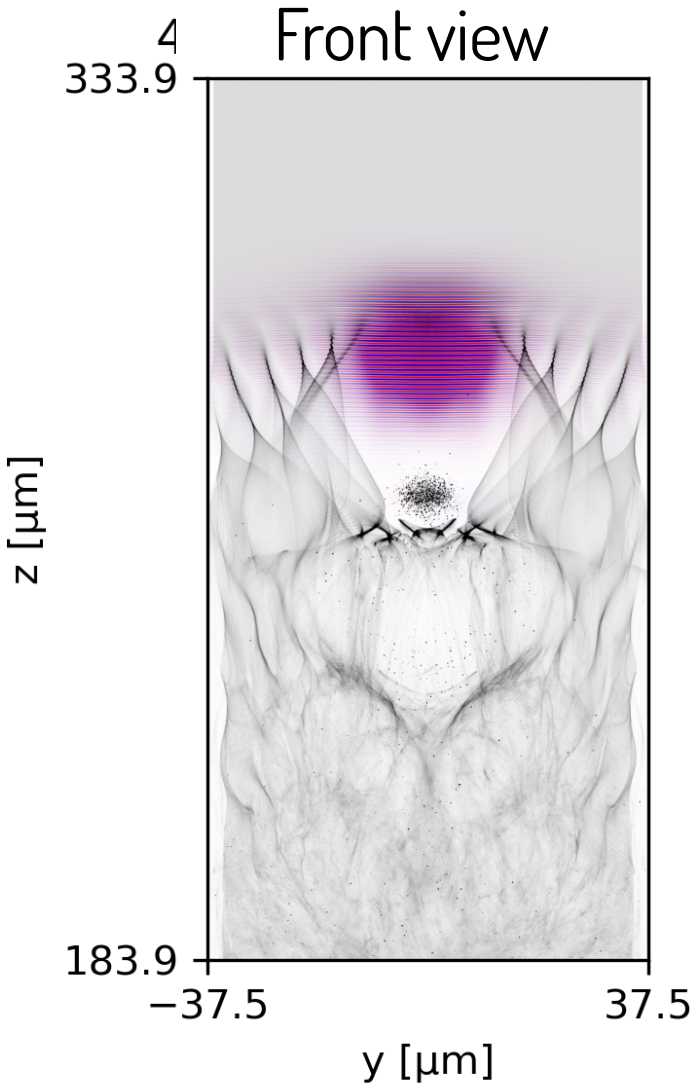

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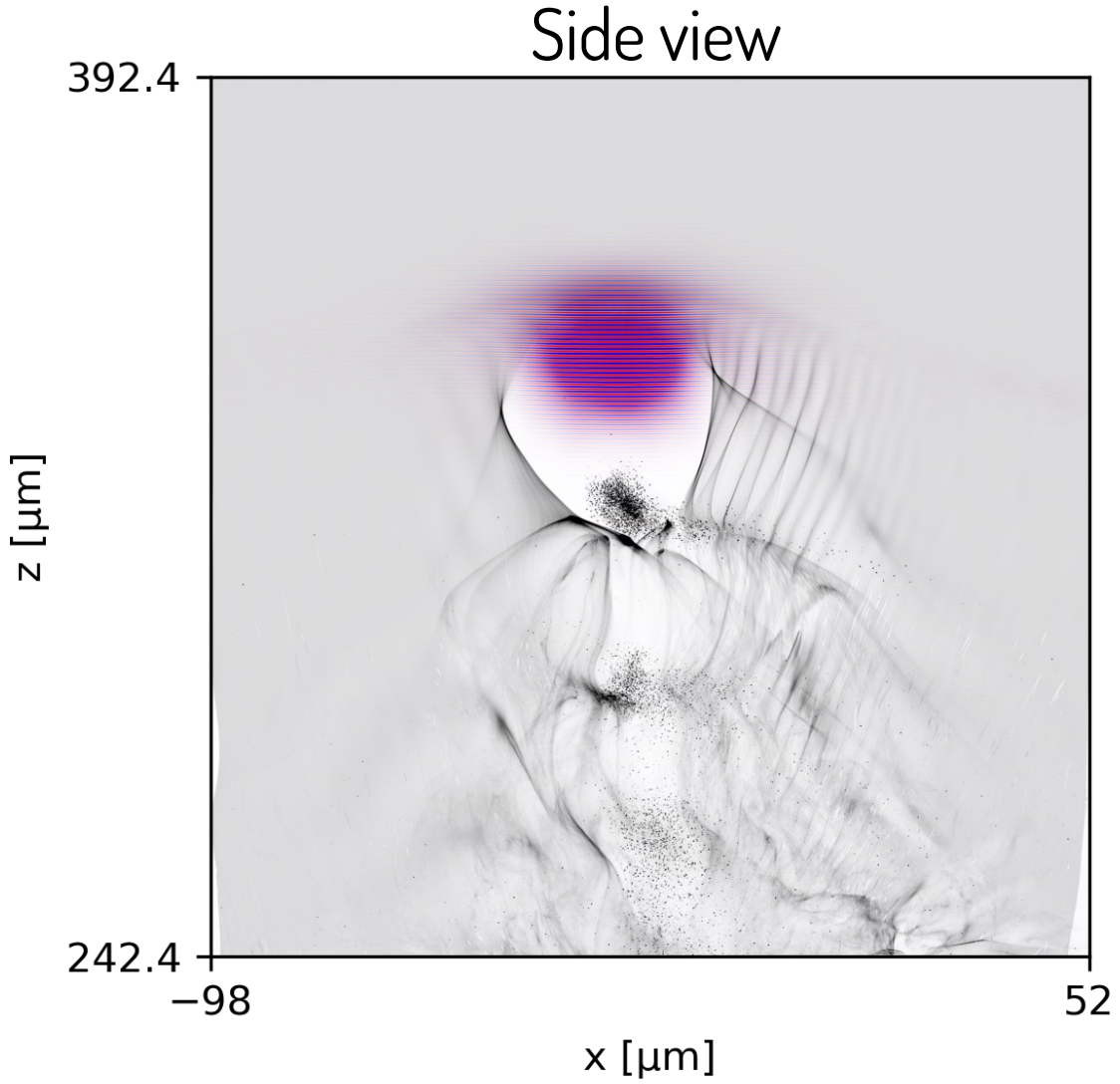

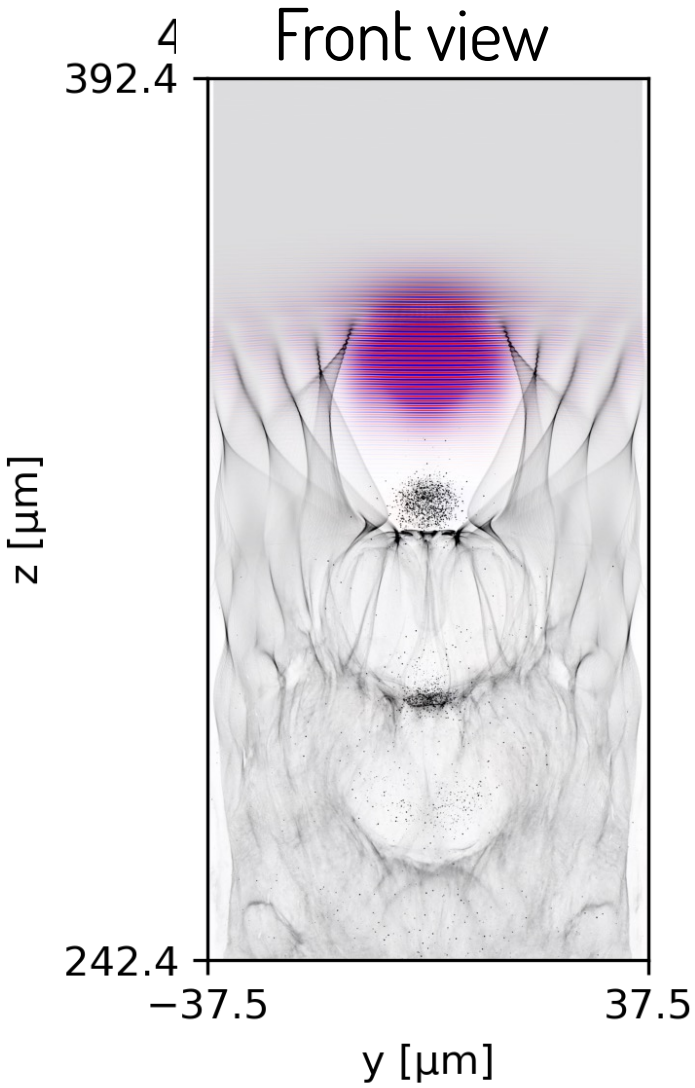

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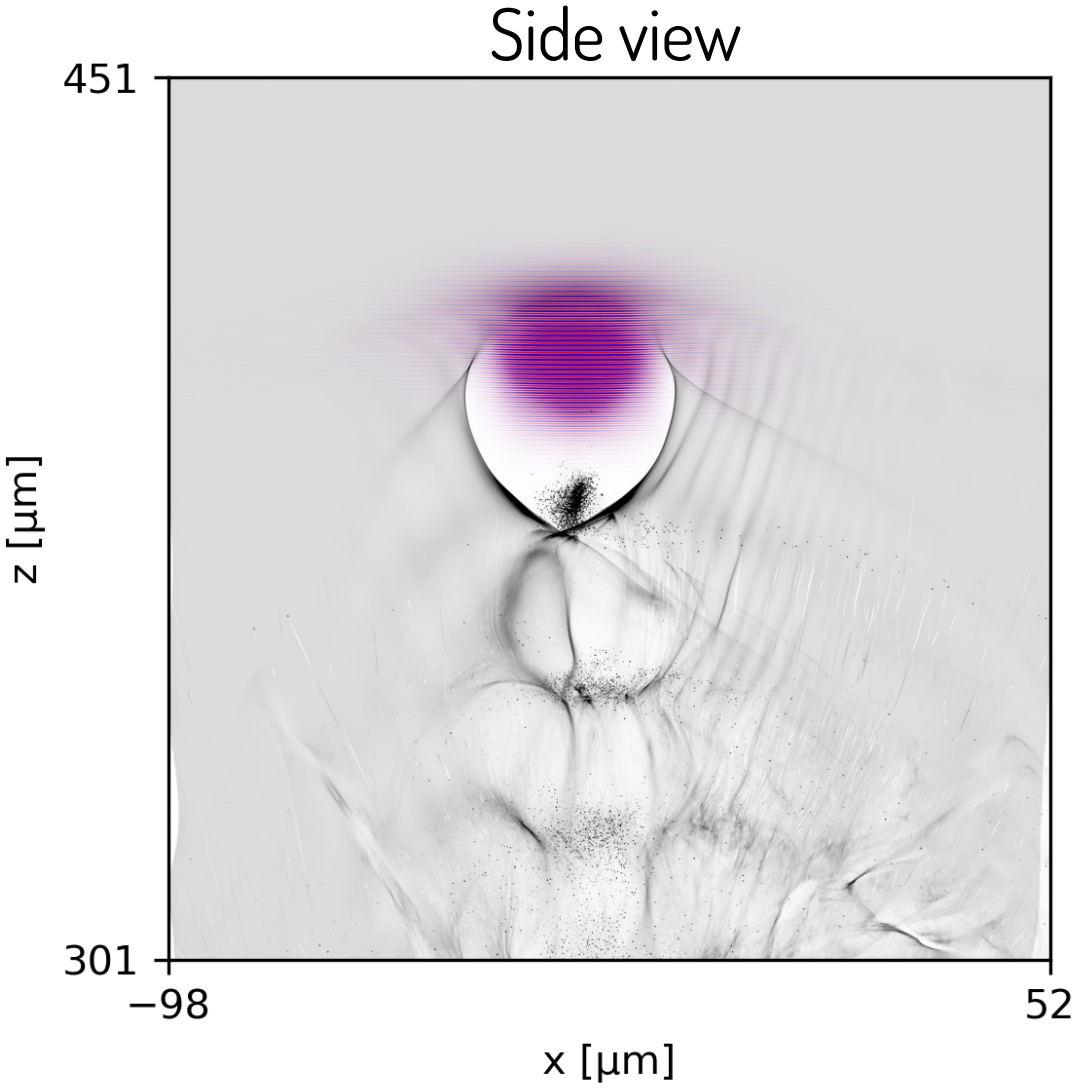

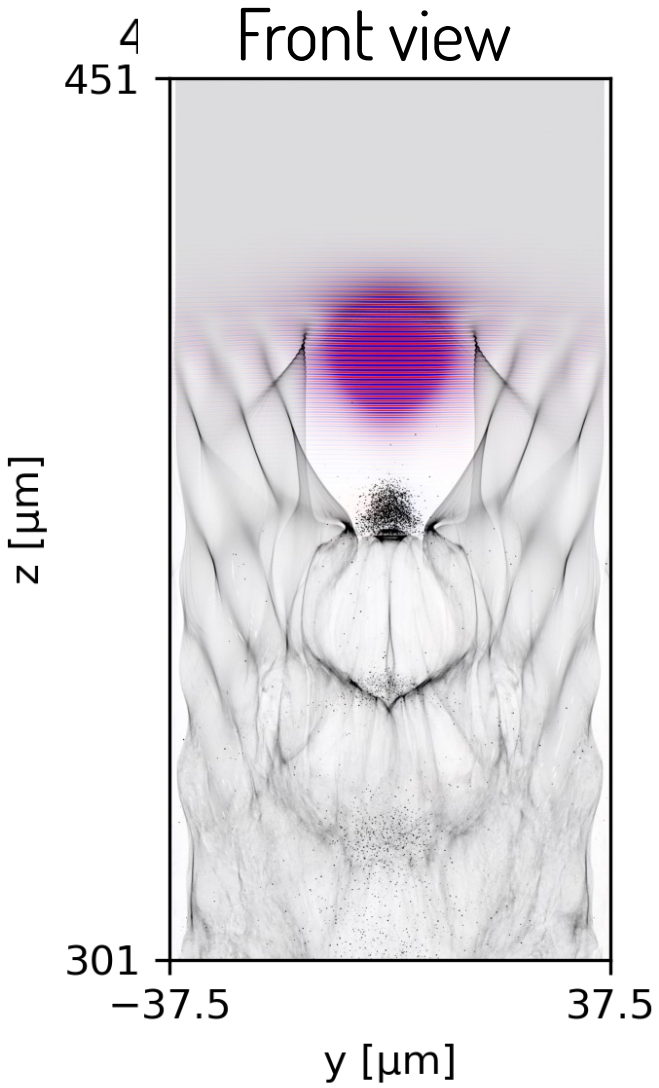

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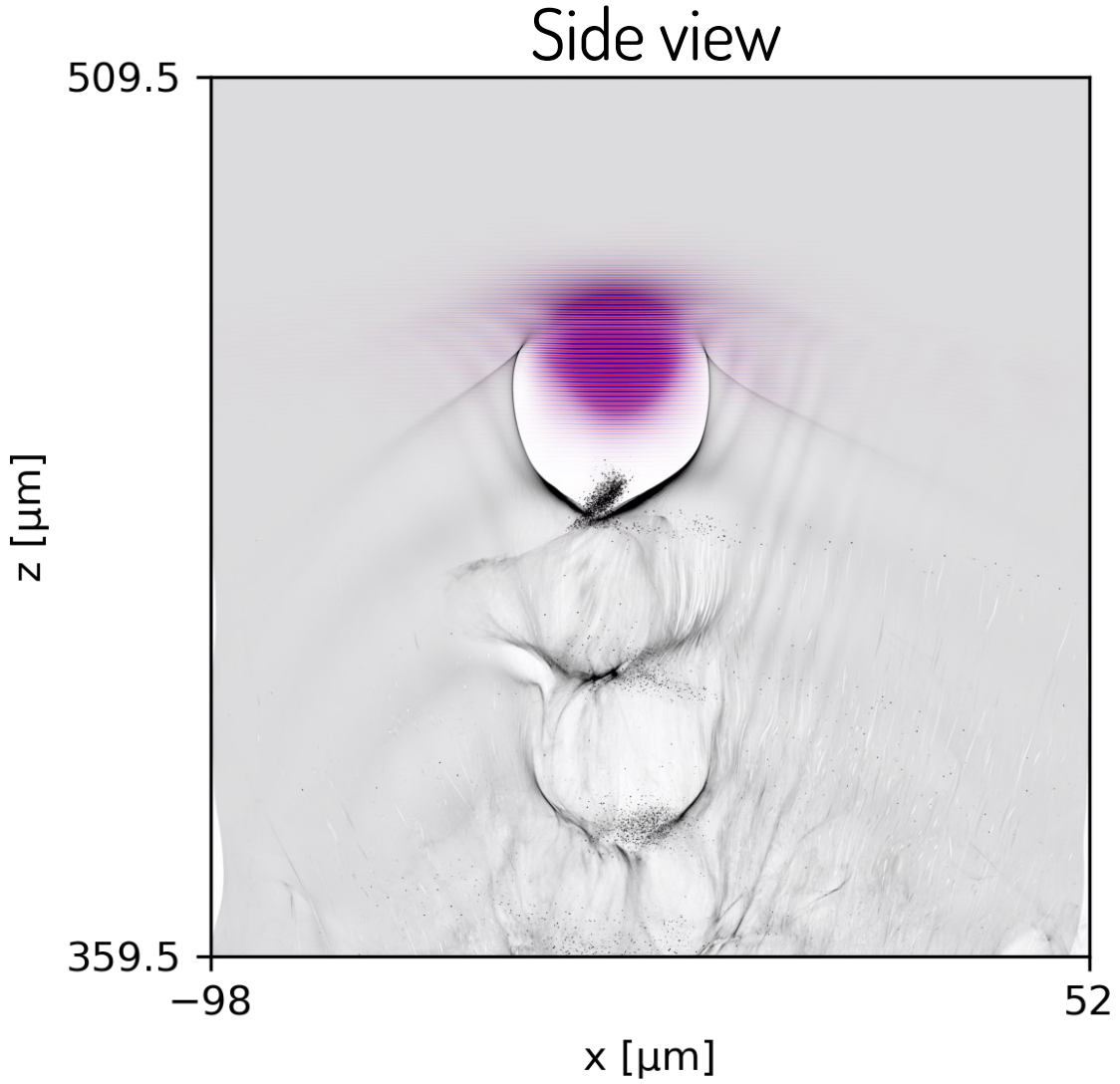

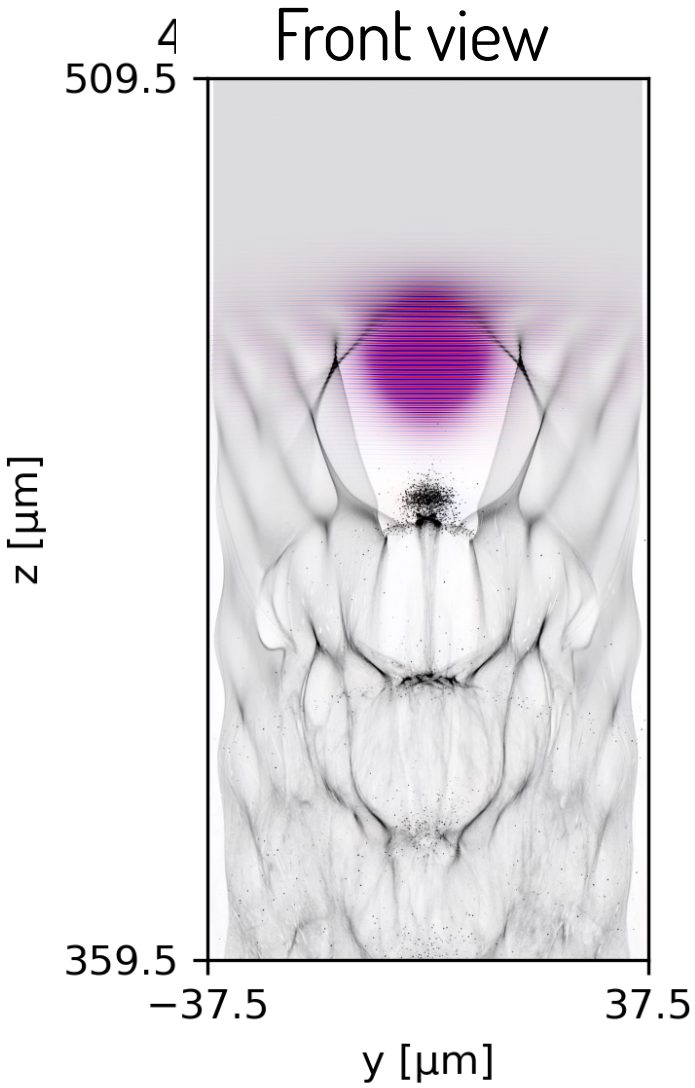

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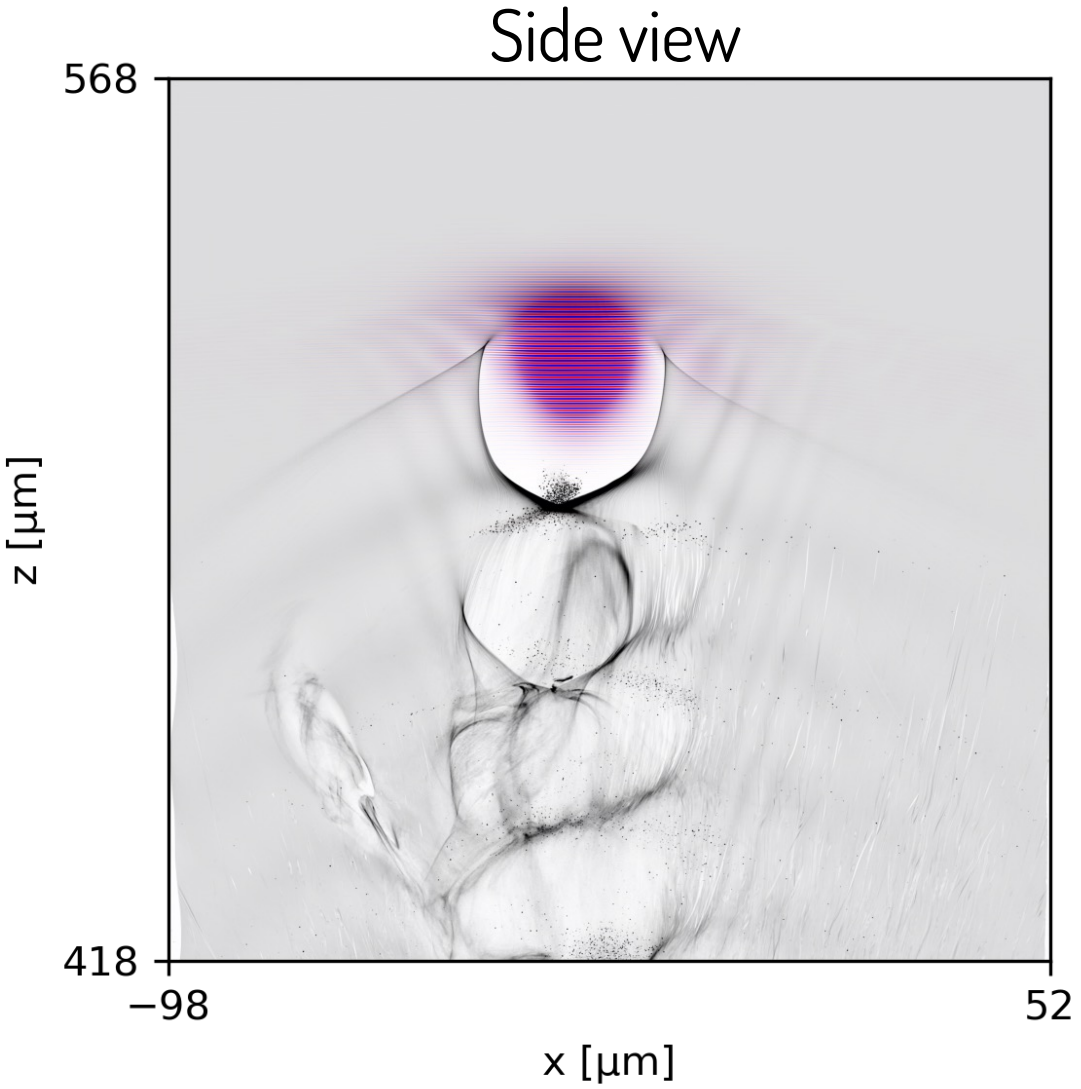

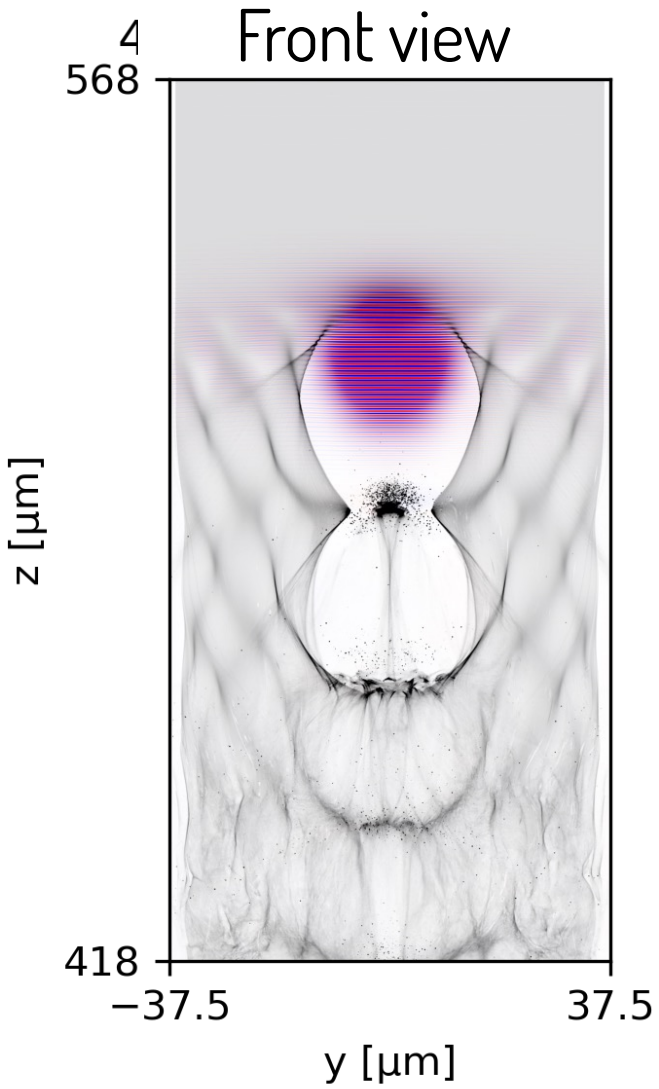

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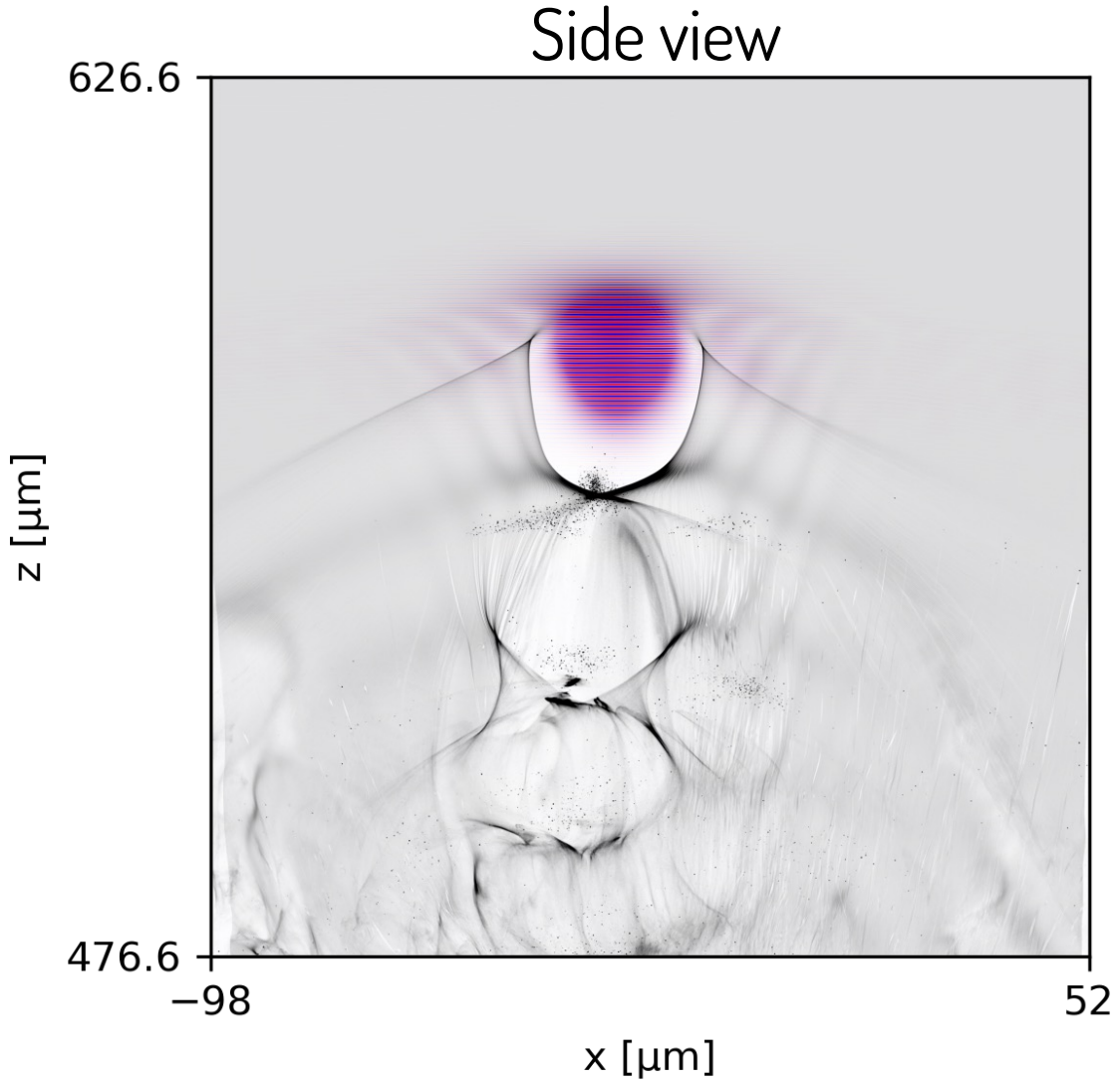

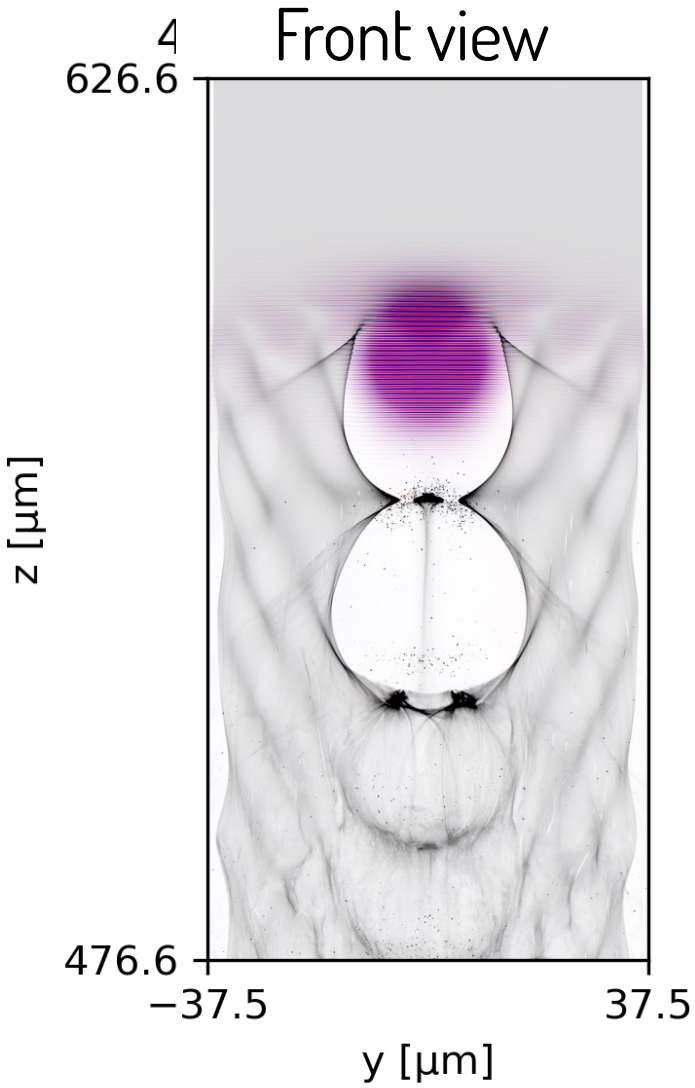

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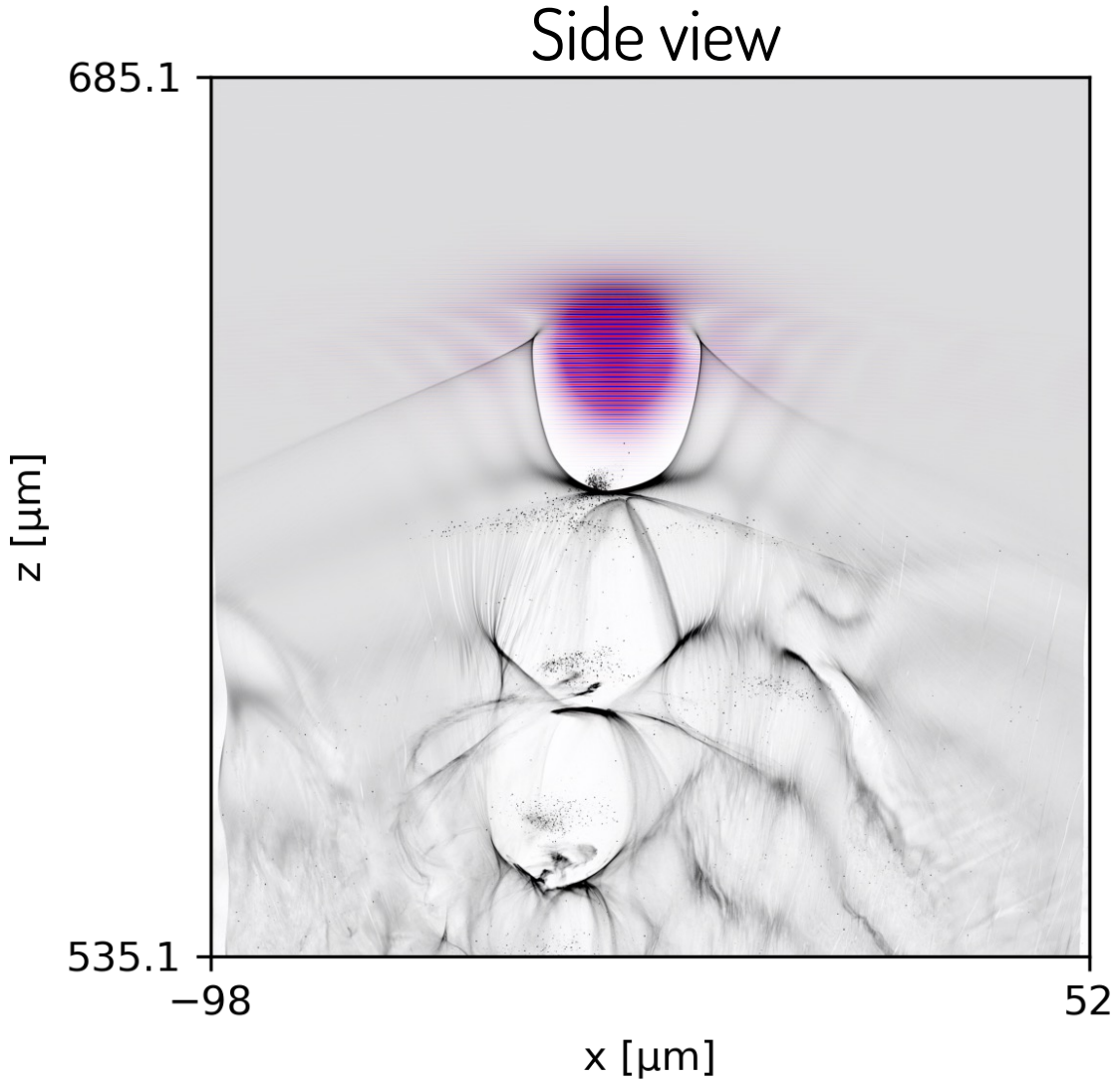

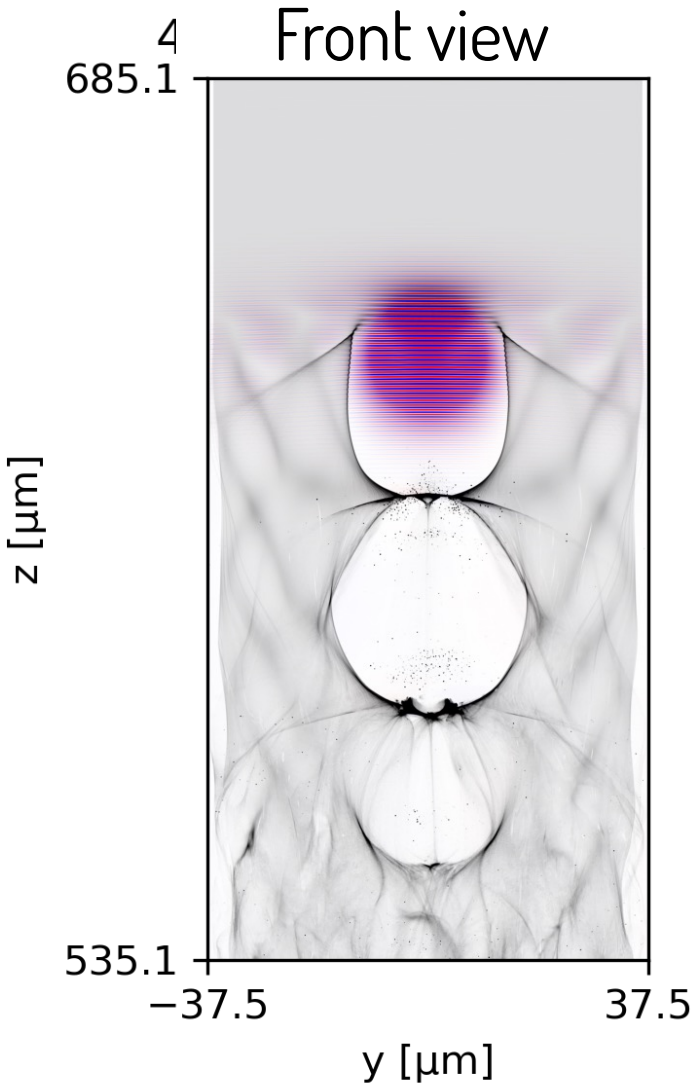

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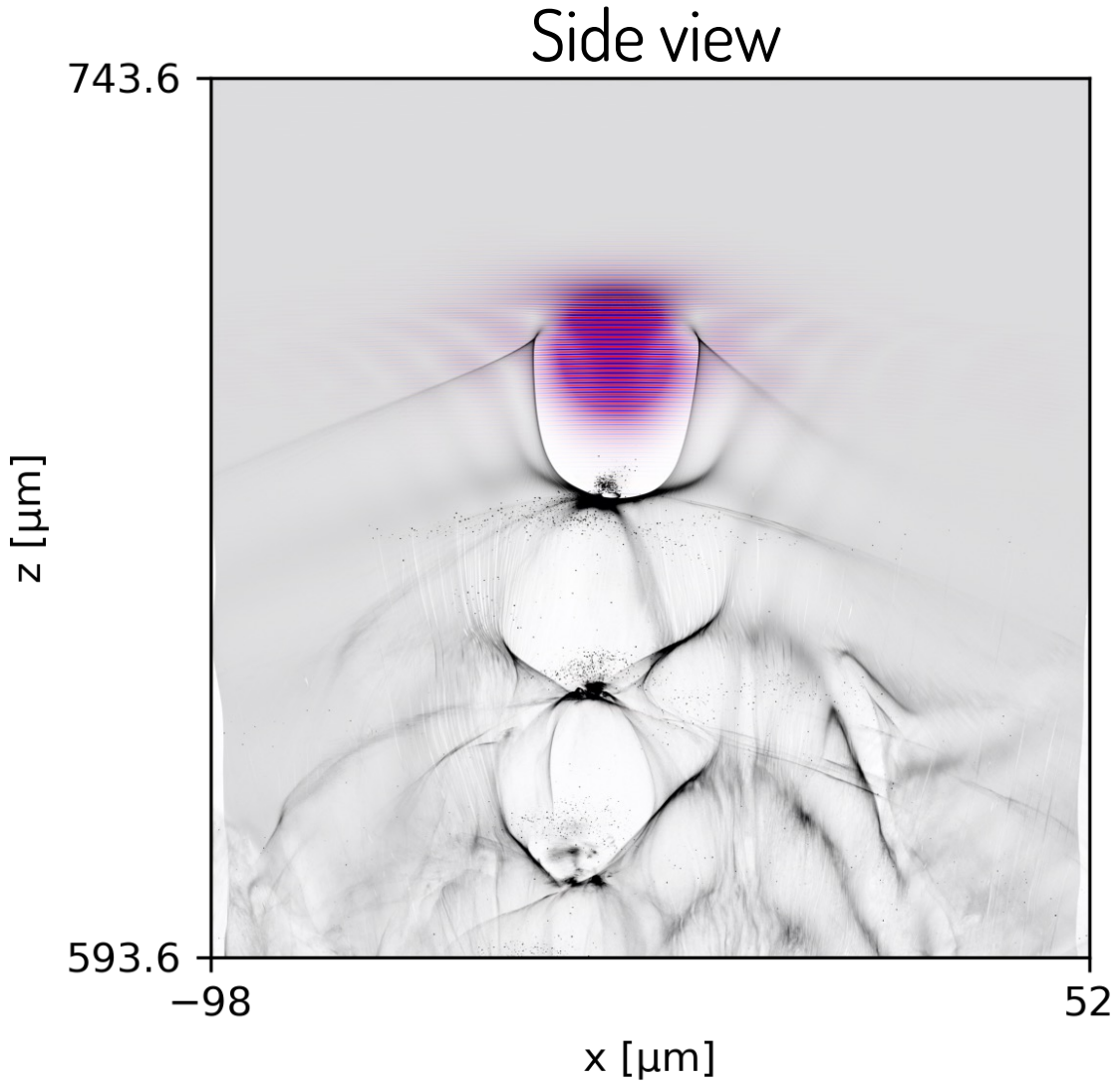

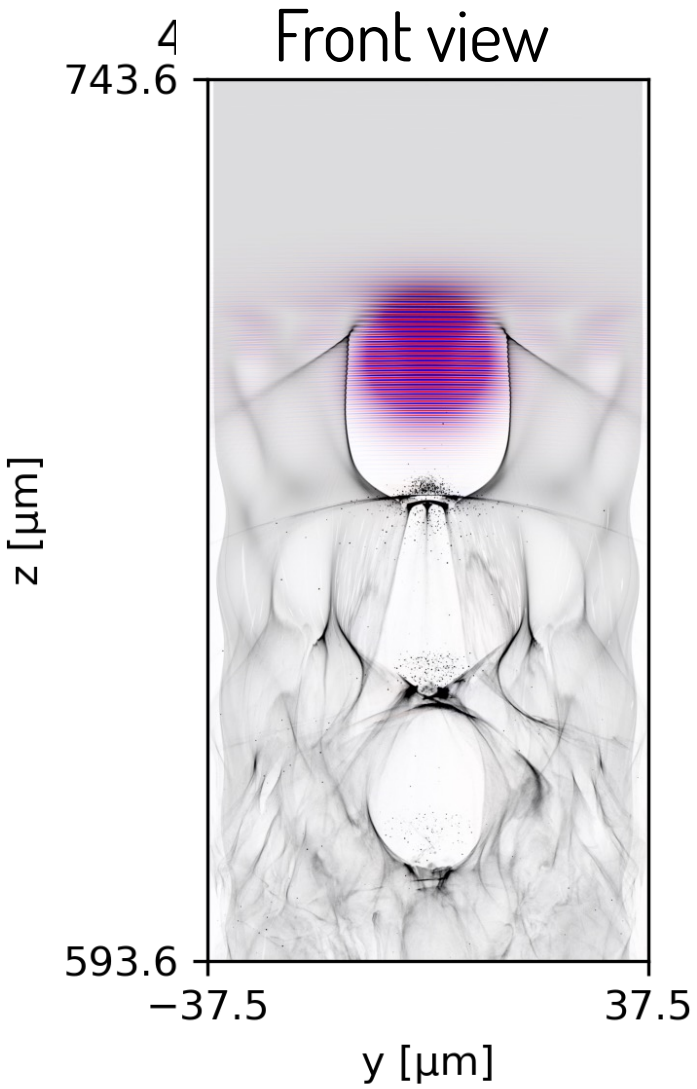

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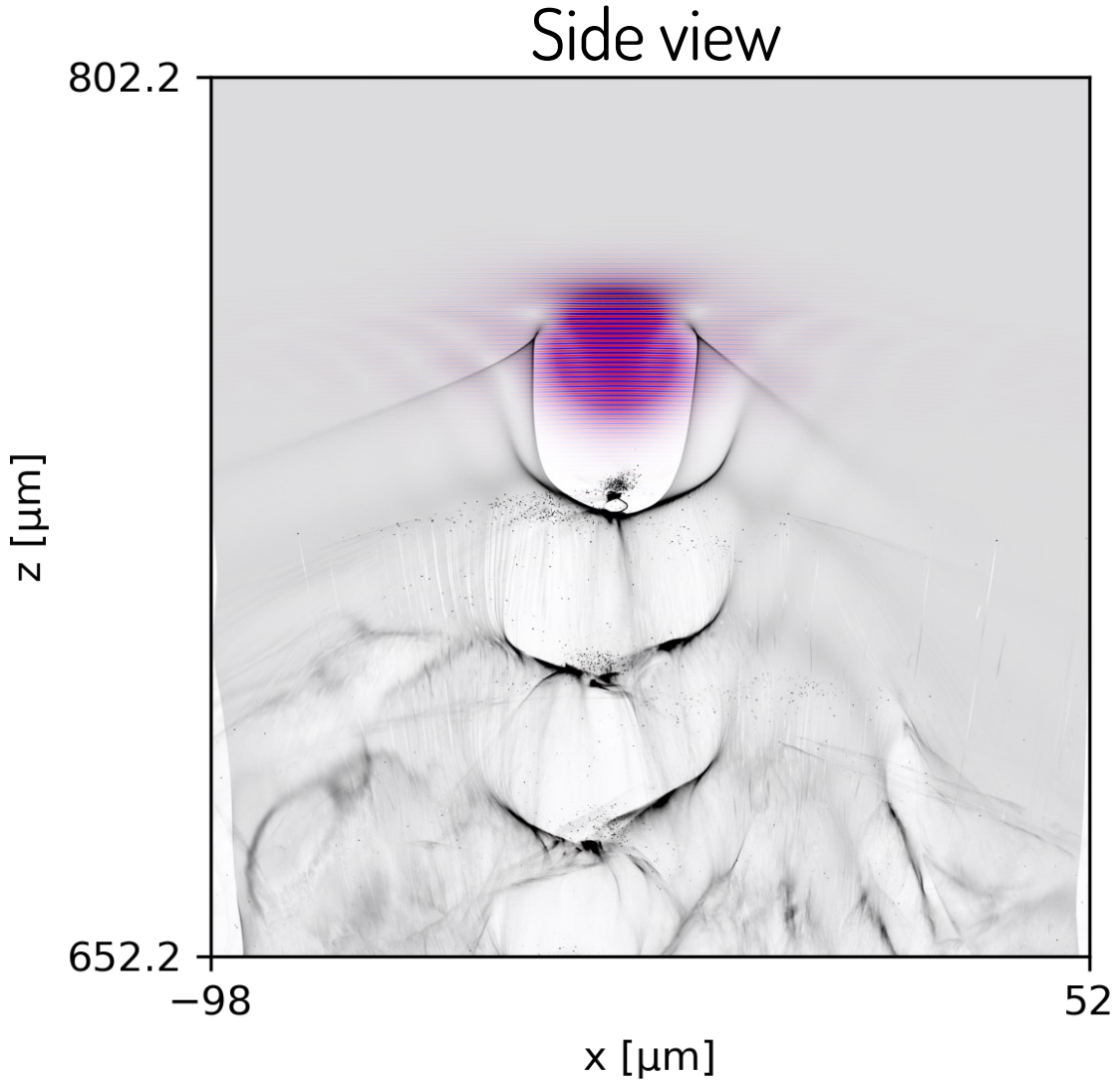

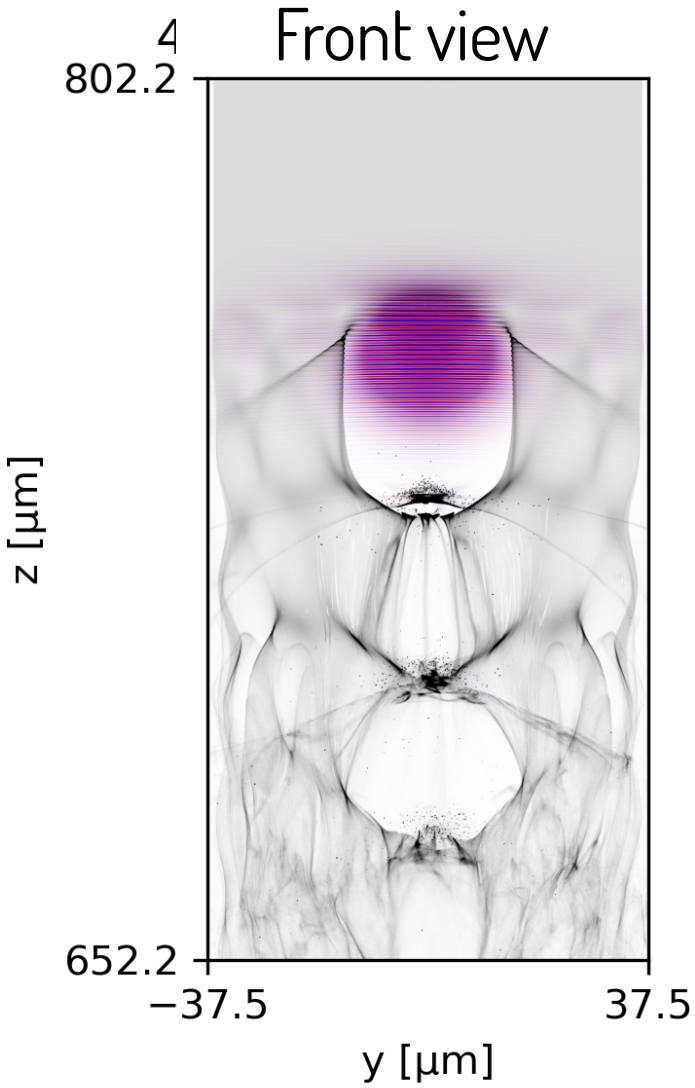

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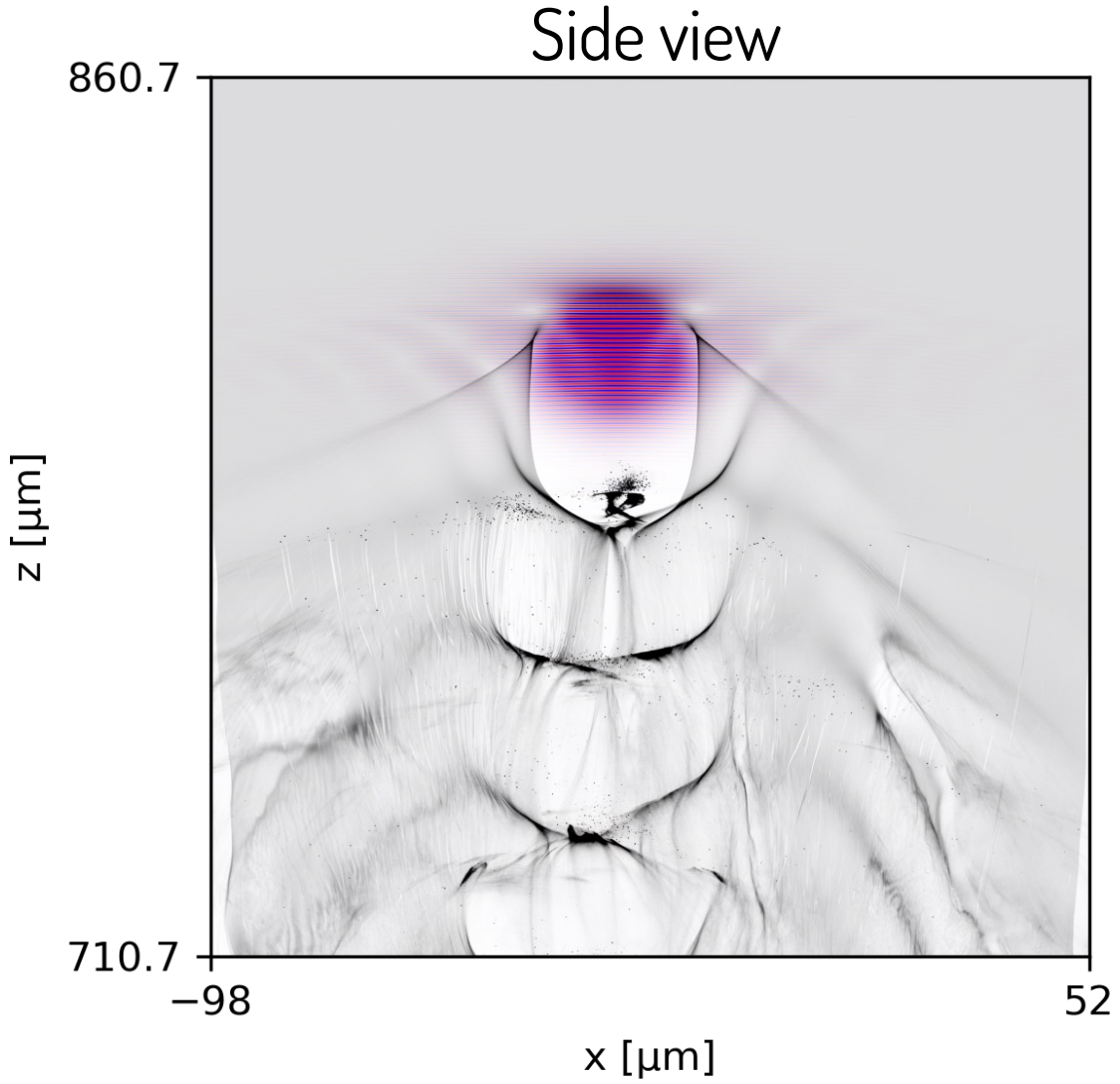

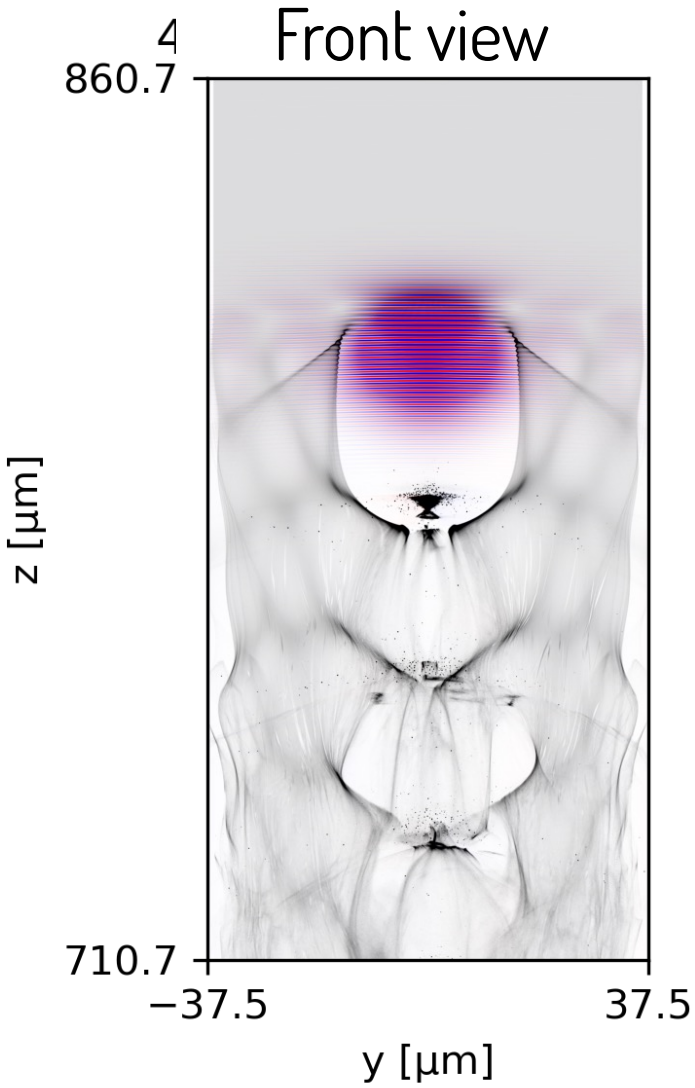

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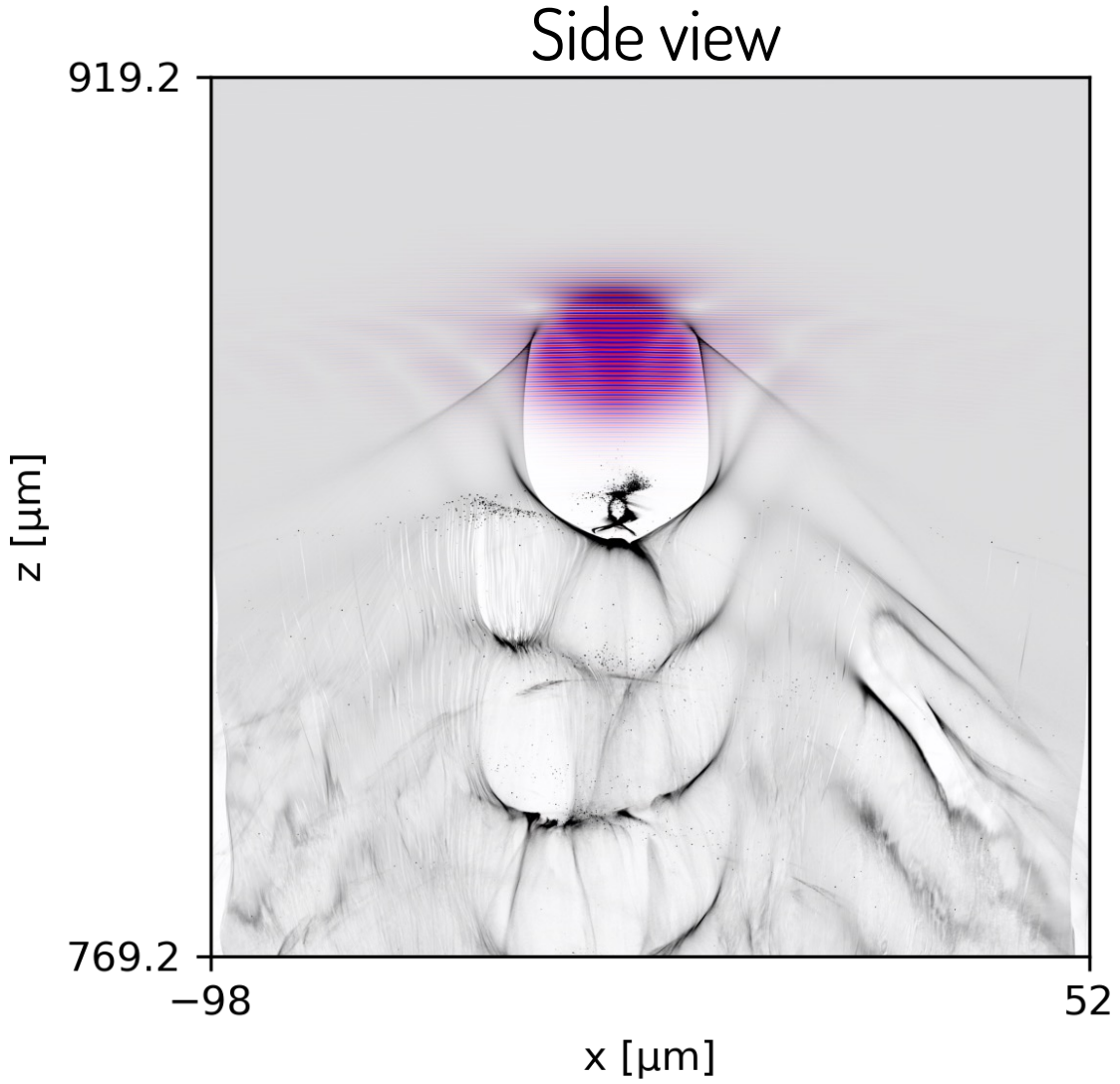

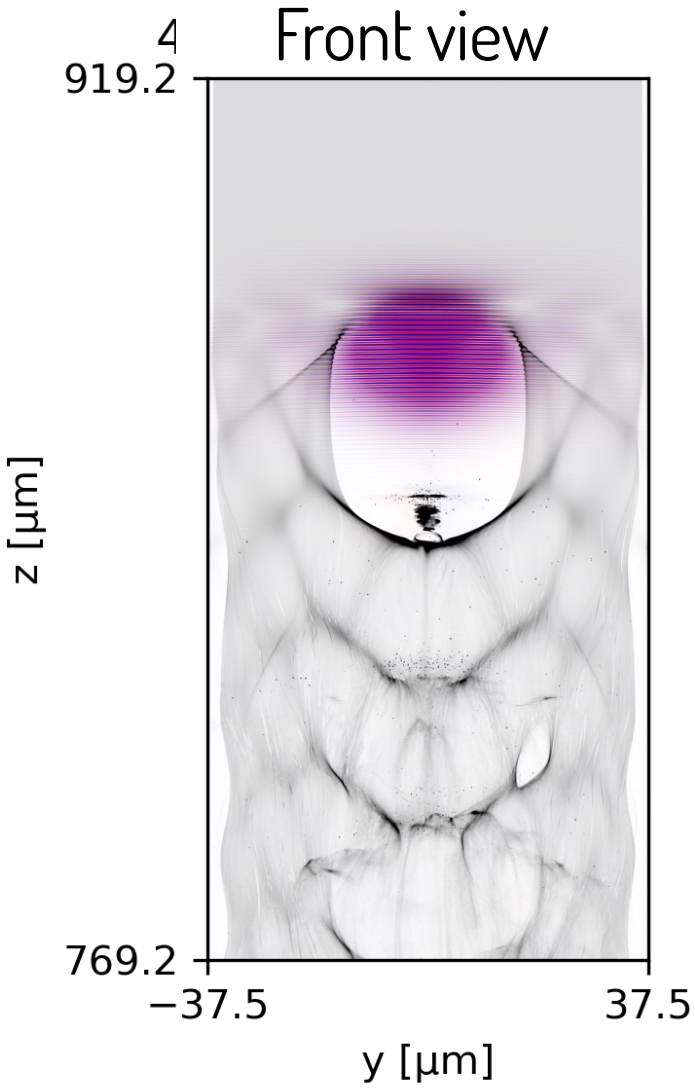

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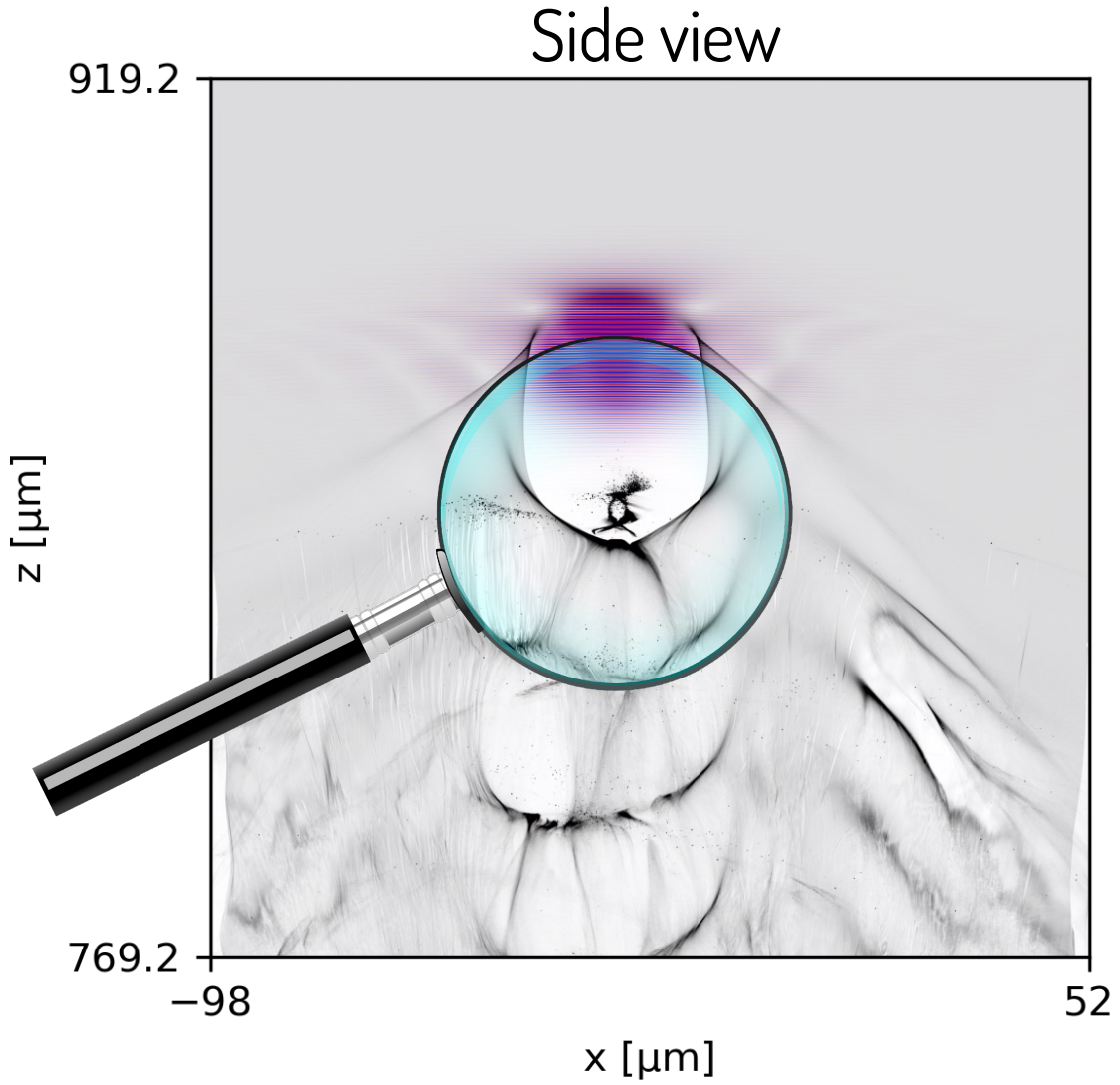
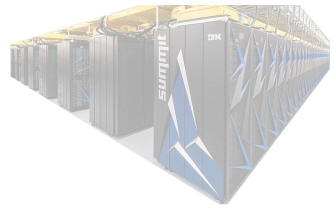
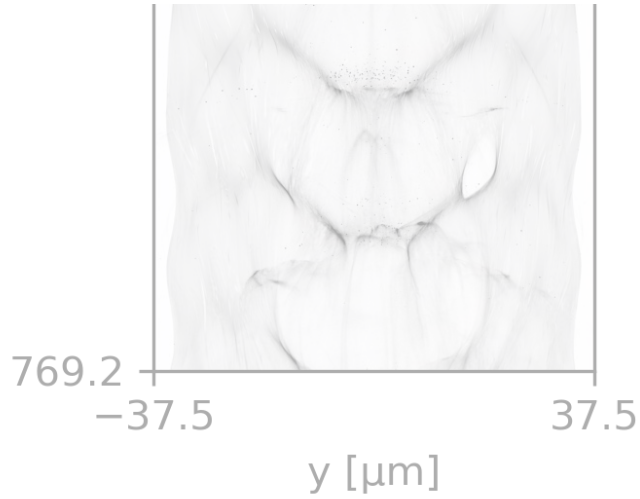
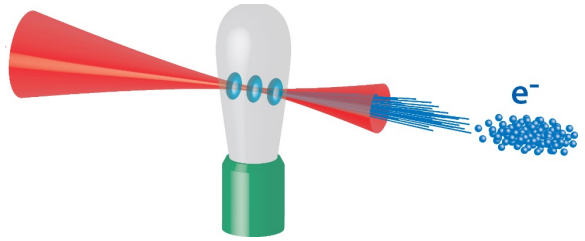




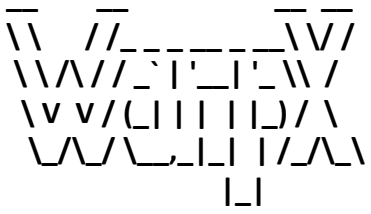
←We are mainly concerned with the properties of these electrons



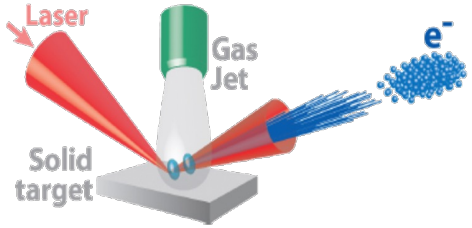
Outline



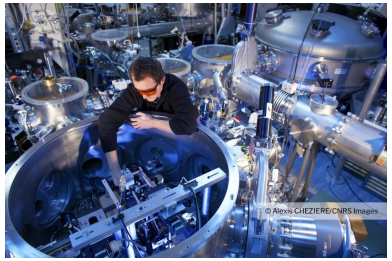
The idea of the Hybrid Target



Simulate the Hybrid Target



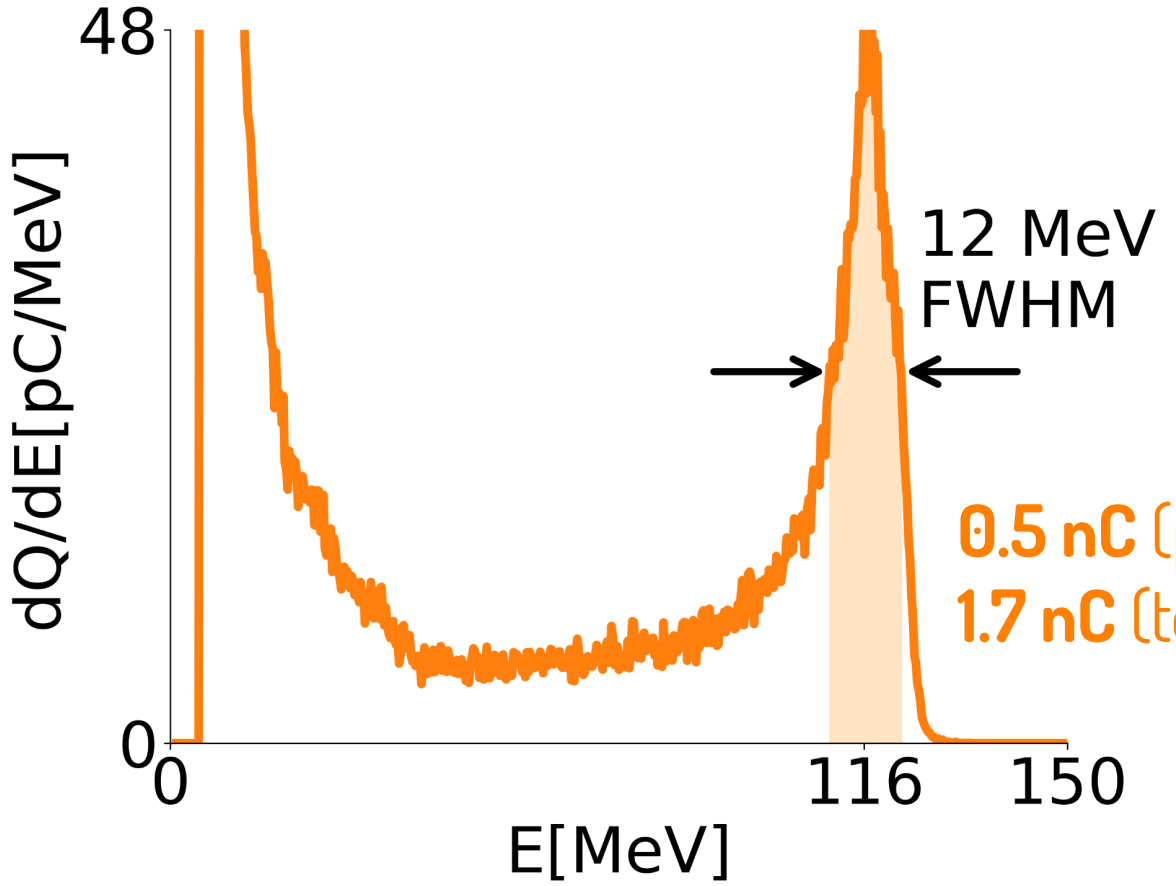
Numerical study



Experimental validation

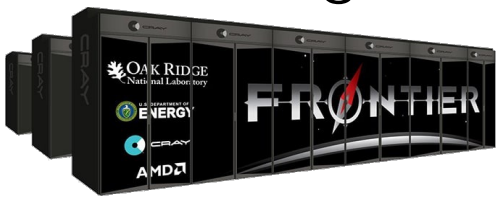
Our simulations with a PW-class laser show that we can accelerate a substantial amount of charge with high quality

After ~ 1mm
(acceleration still in progress)



0.5 nC (peak) for a
1.7 nC (total) **PW laser**

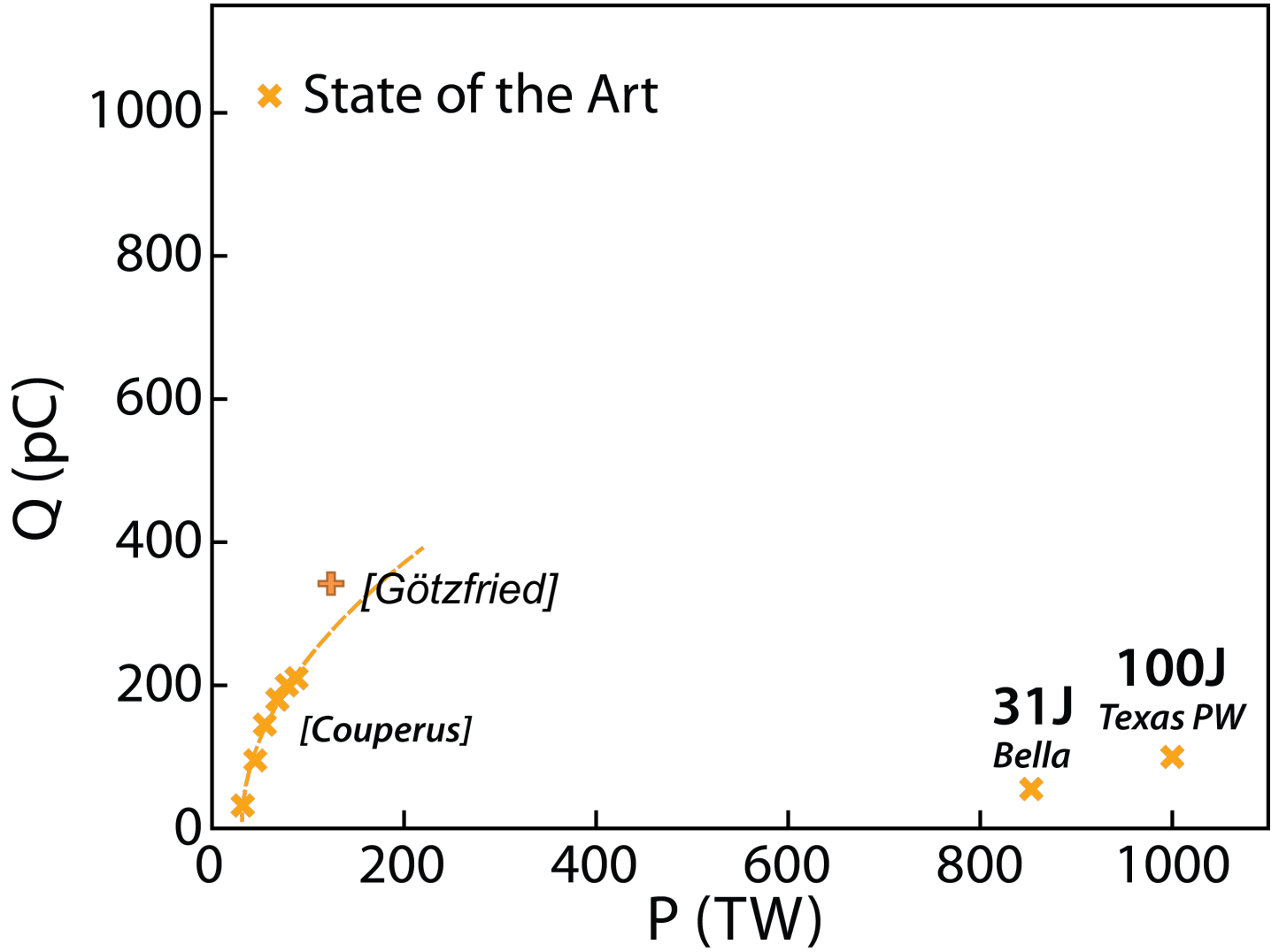
Production runs on
Frontier, Fugaku and Summit



With the hybrid target we can accelerate a lot of charge at high energy !

- Study with PIC simulations

Complicate to accelerate high charge on high power lasers with conventional techniques



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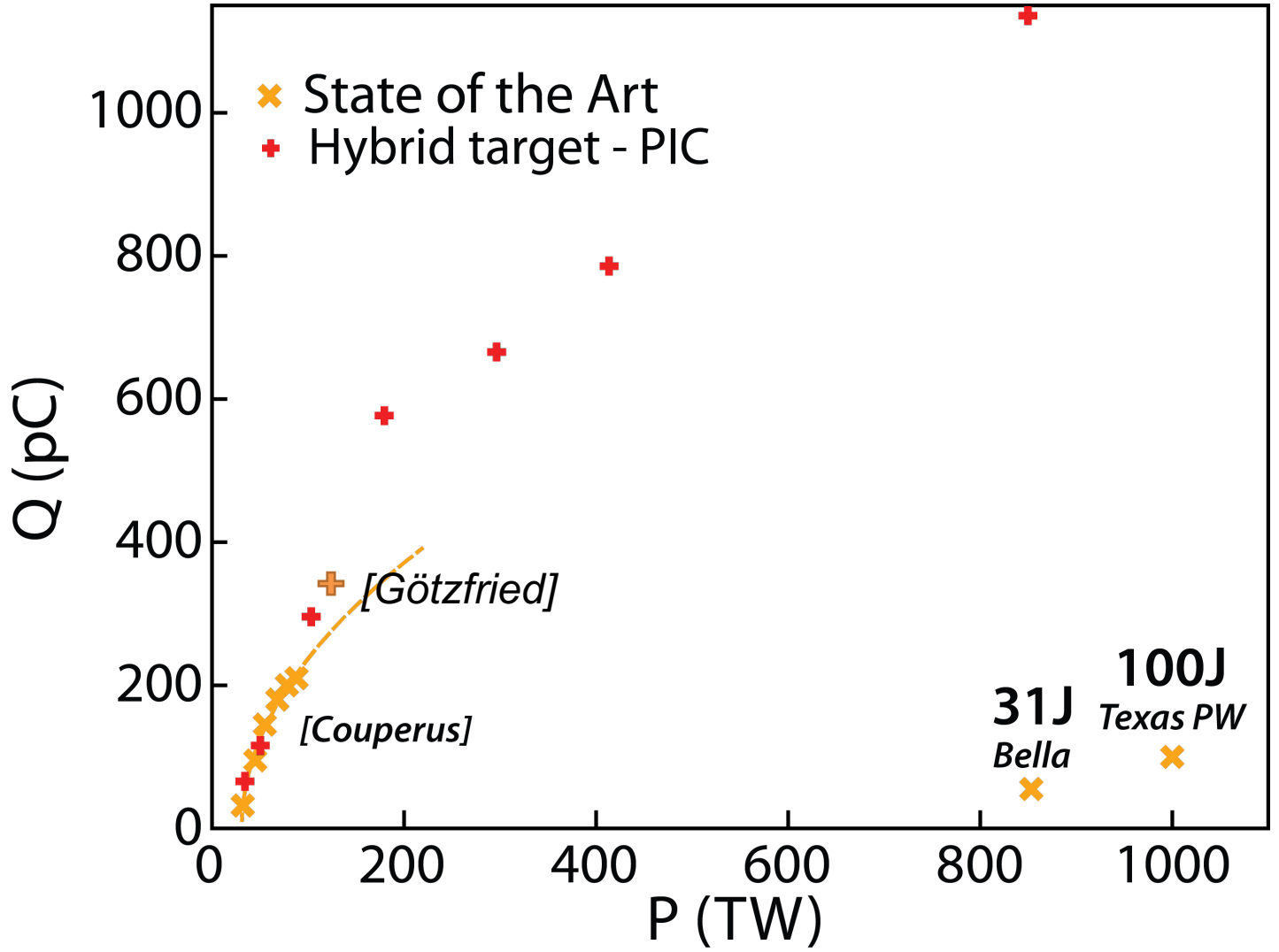

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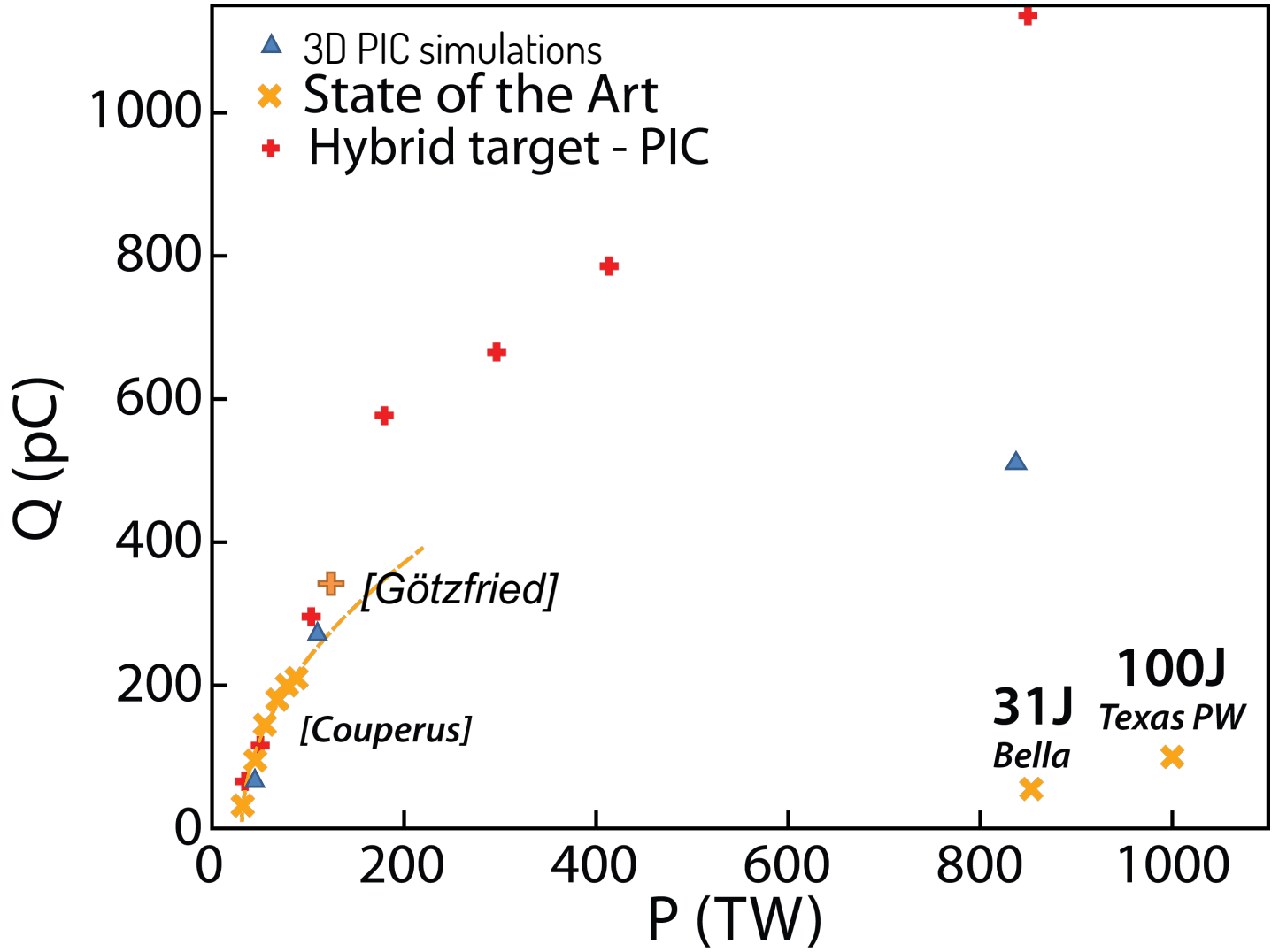

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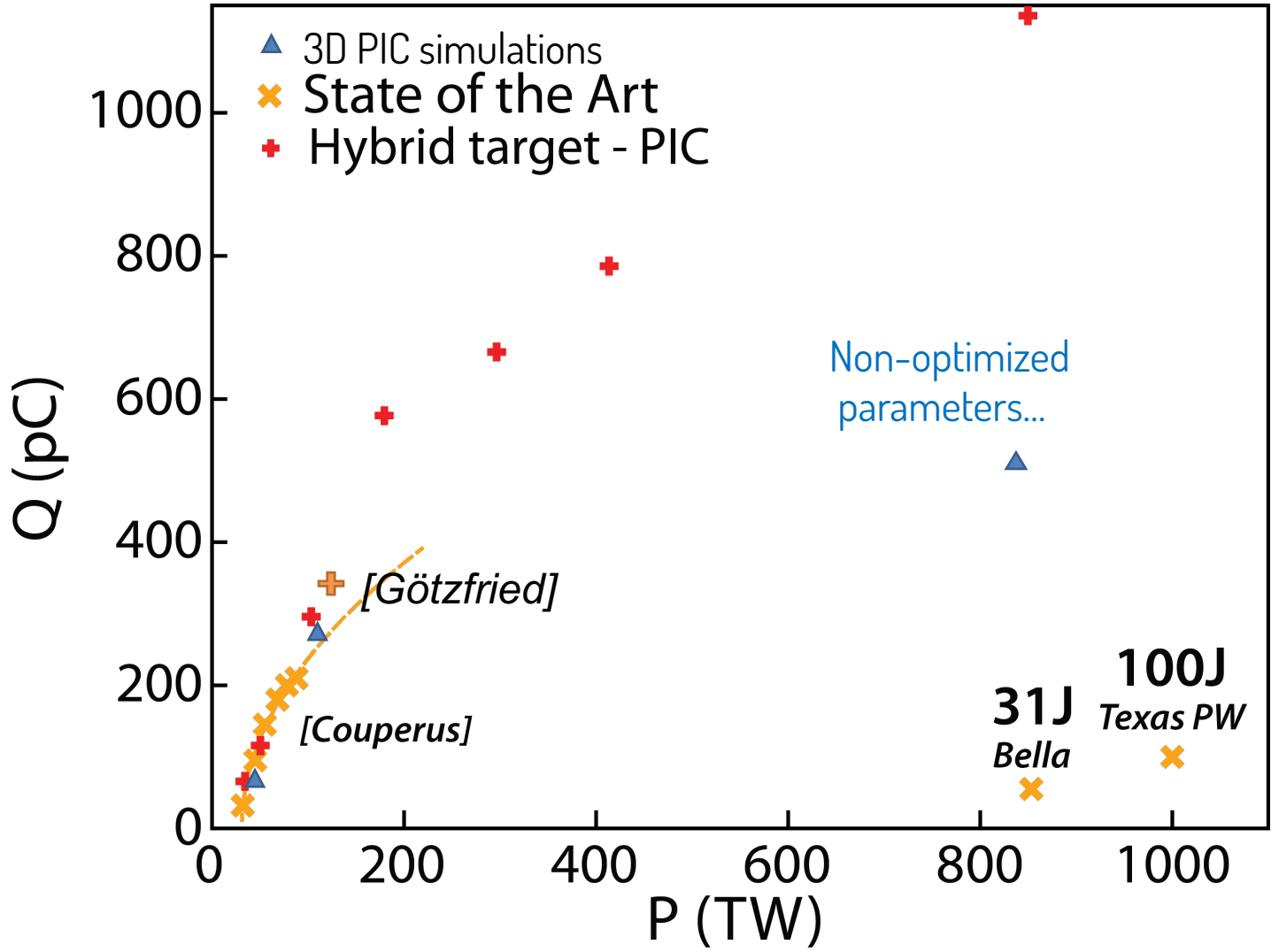

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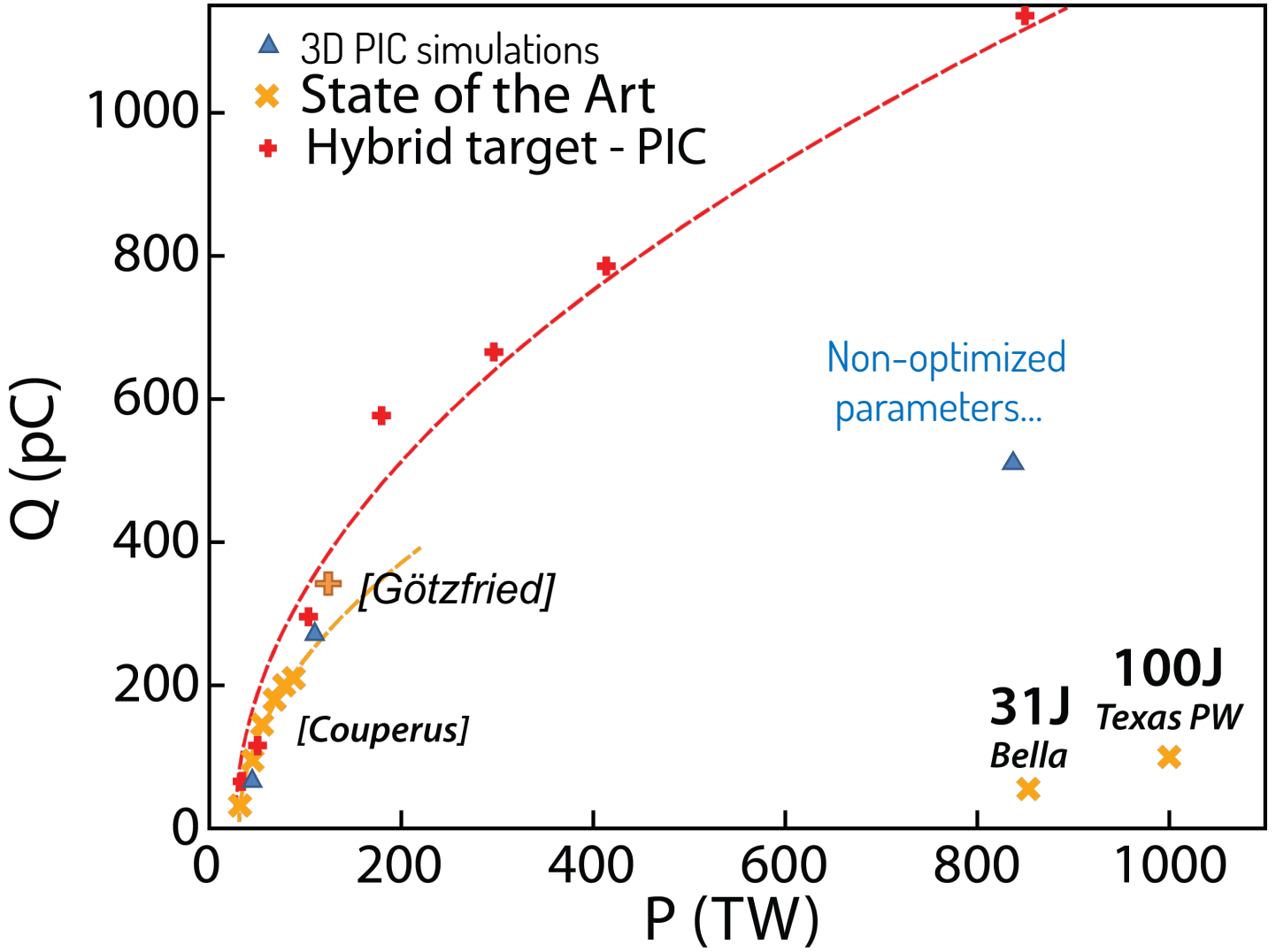
Complicate to accelerate high charge on high power lasers with conventional techniques

Higher charge than other techniques !



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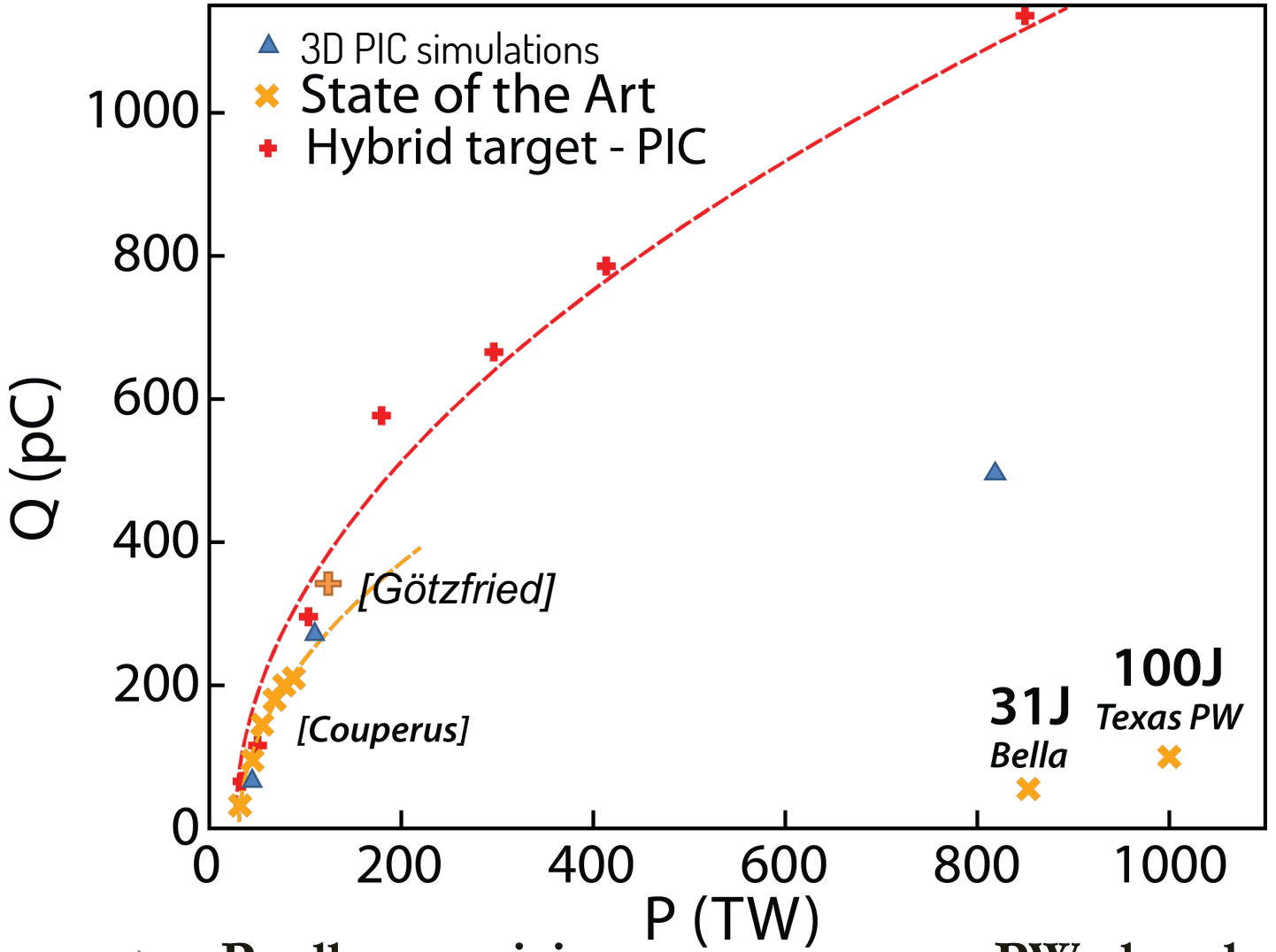


- **Really promising, even more on PW class laser !**

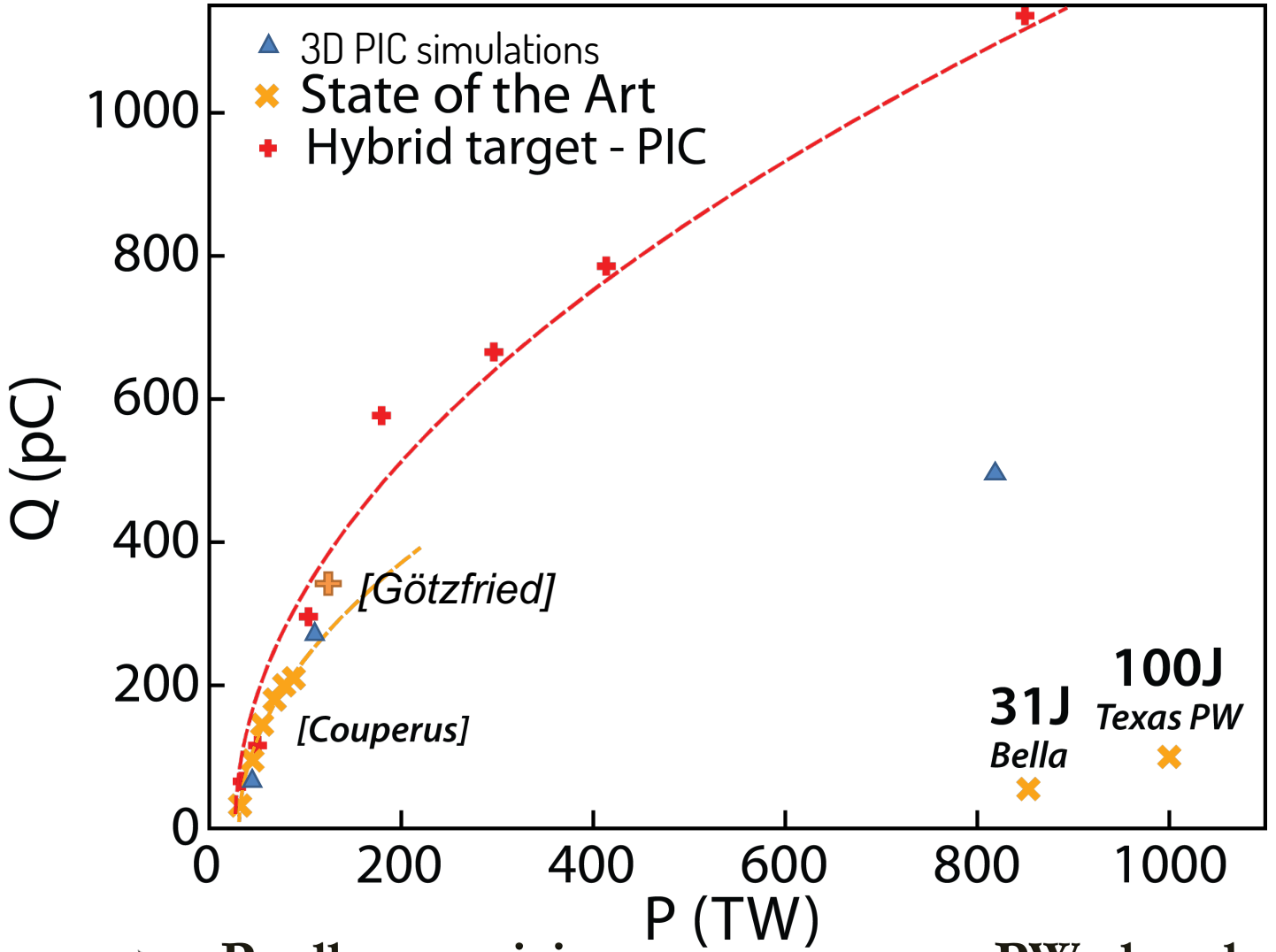
With the hybrid target we can accelerate a lot of charge at high energy !

- **Study with PIC simulations**

Complicate to accelerate high charge on high power lasers with conventional techniques

Higher charge than other techniques !

With also a good energy spread (between 4 and 10%)

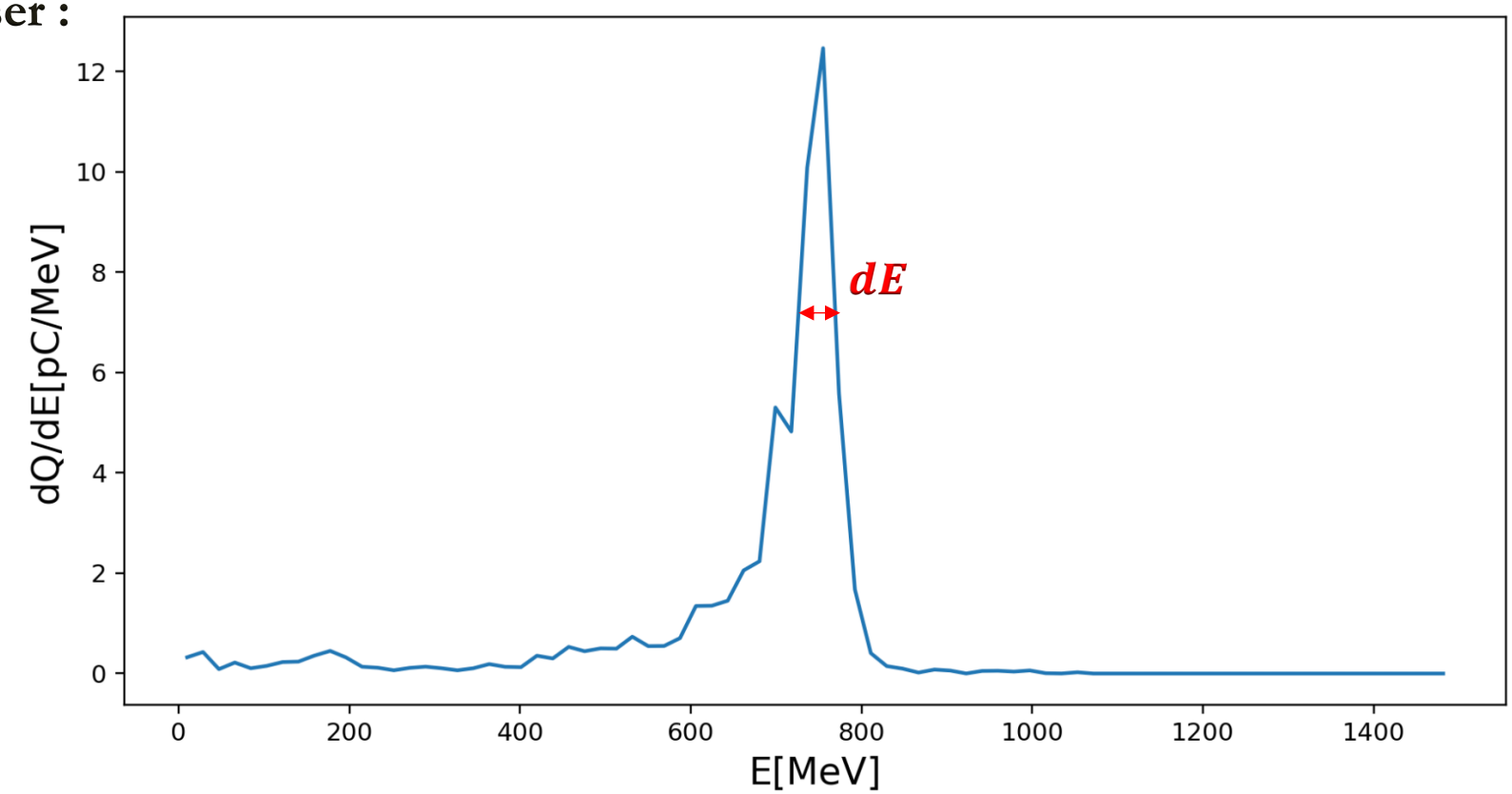


- **Really promising, even more on PW class laser !**

With the hybrid target we can accelerate a lot of charge at high energy !

- **What does it give on PW class laser :**

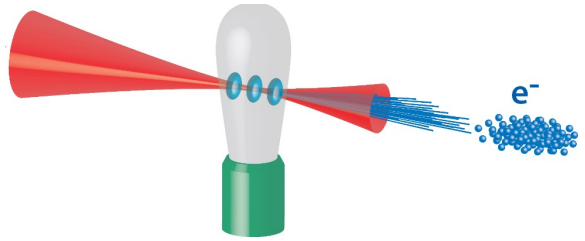
For Laser parameters as Bella installation (30J)



- **Nanocoulomb charge beam at high energy !**

Q =1.1 nC E_{peak} **=758 MeV** $\frac{dE}{E_{peak}} \sim 5\%$

Outline



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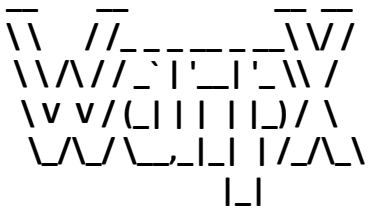
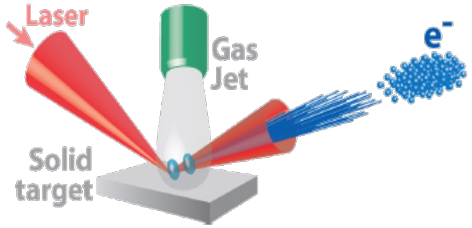


WarpX : an exascale PIC code



Numerical study

Experimental validation

Exascale simulations informed the design of the first experimental validation of our concept (at LOA)

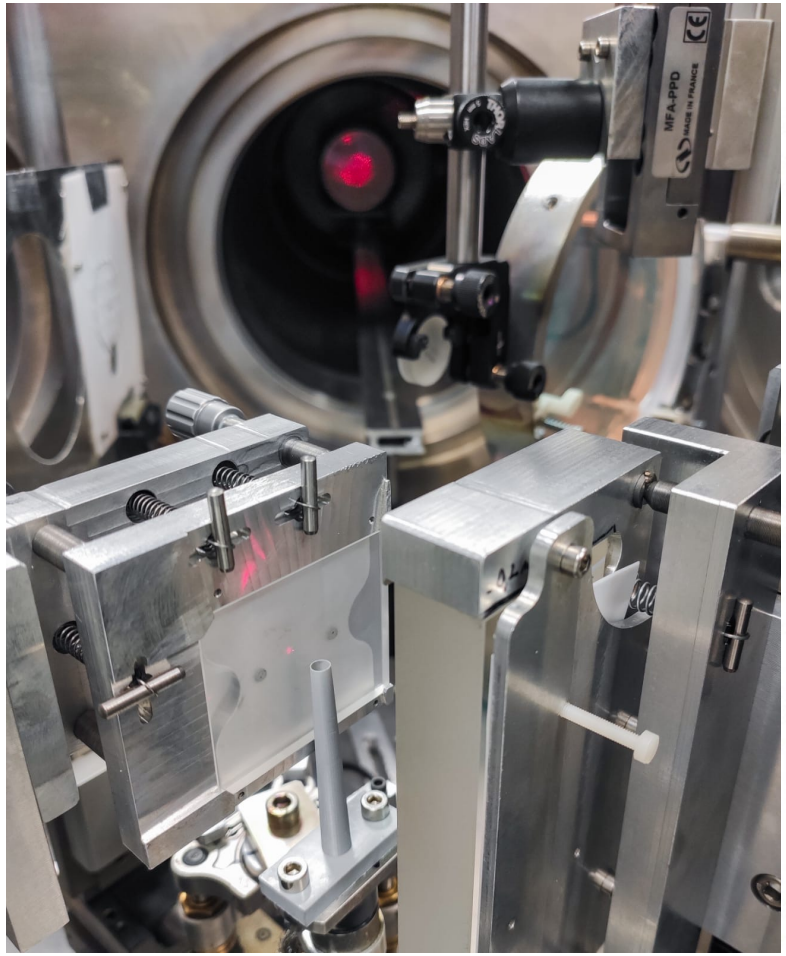
With Adrien Leblanc, UPX

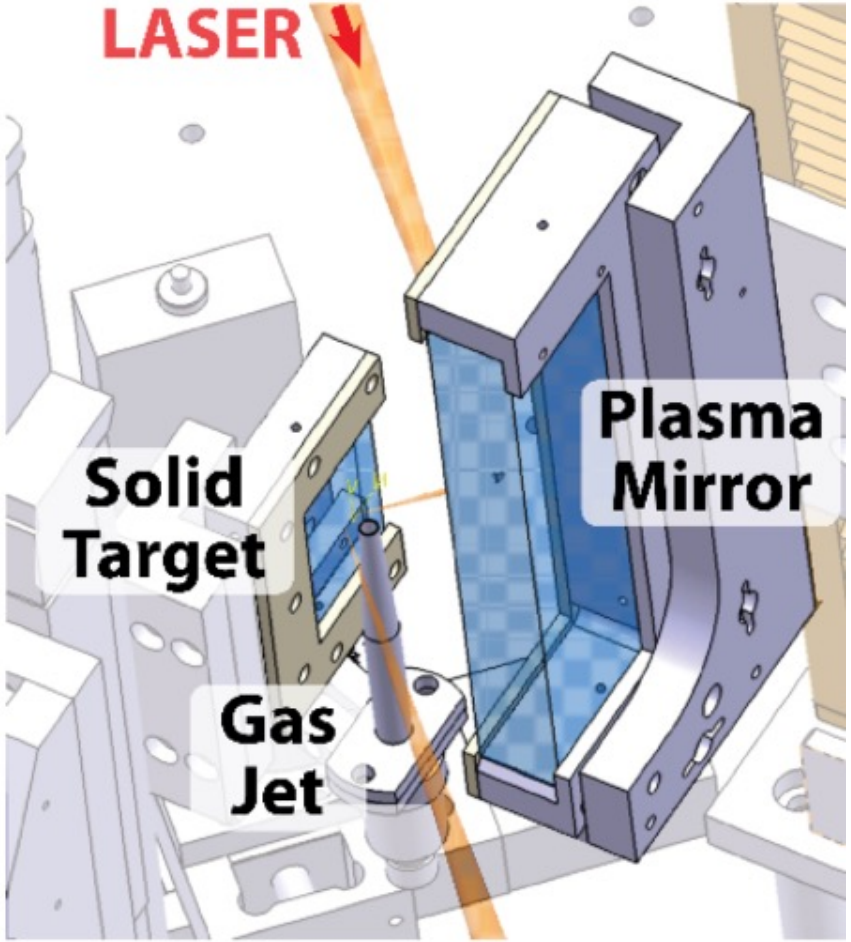
Laser parameters

E = 400 mJ

waist = 17 µm

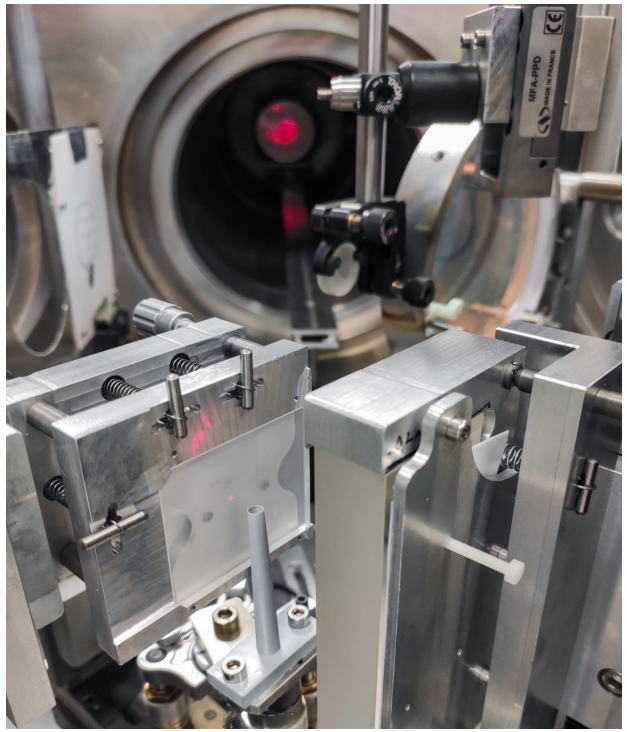
P_{peak} = 10 TW





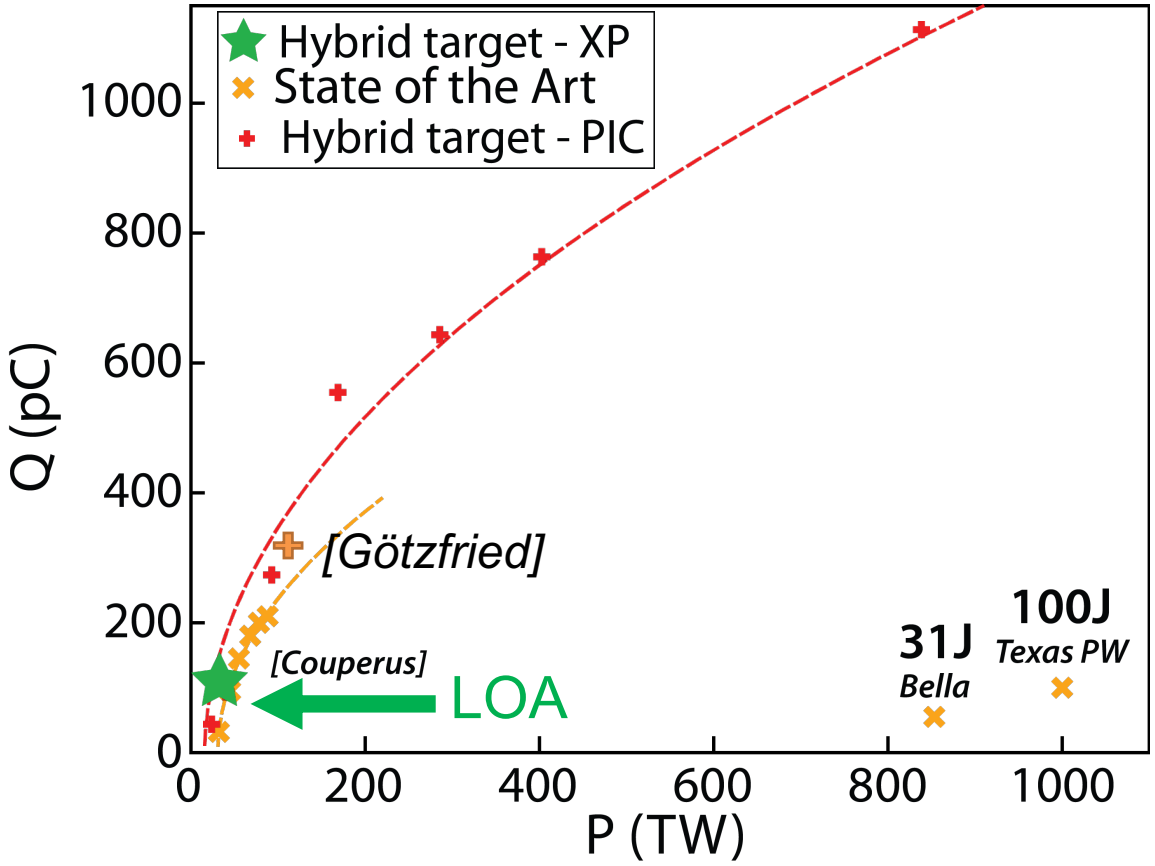
Exascale simulations informed the design of the first experimental validation of our concept (at LOA)

- **The simulations also help us to design the next experiments**

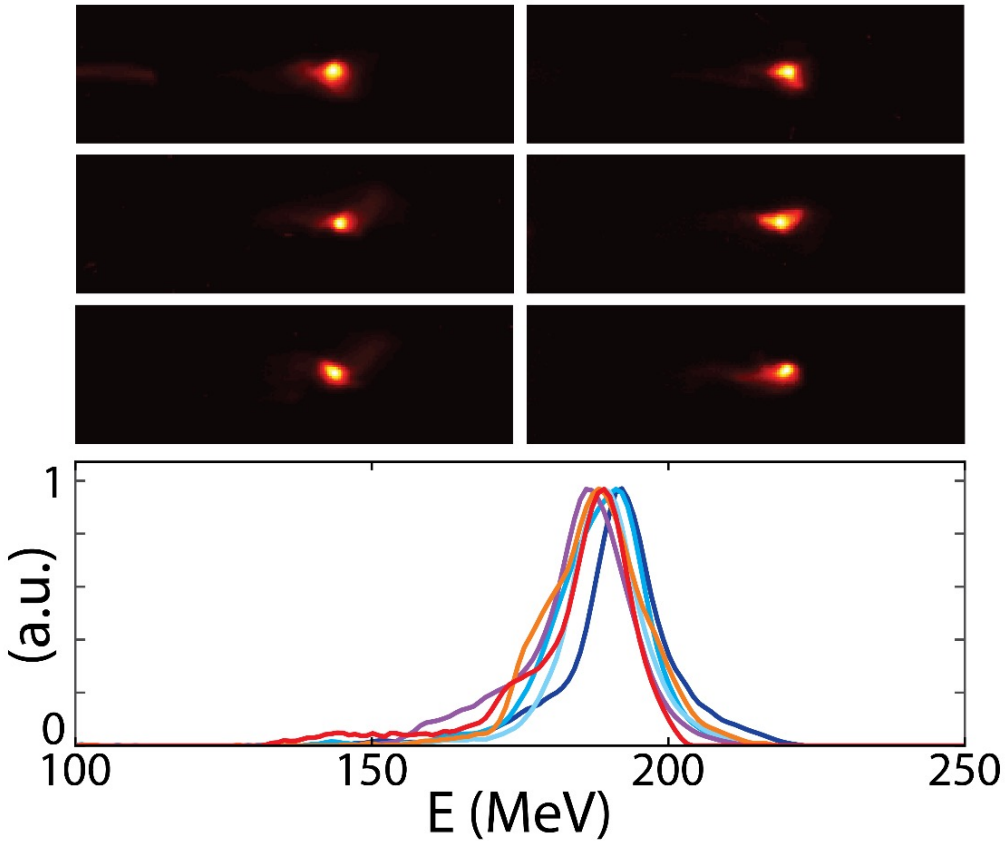


$$E = 0.4J$$

$$P_{peak} = 10TW$$



Exascale simulations informed the design of the first experimental validation of our concept (at LOA)



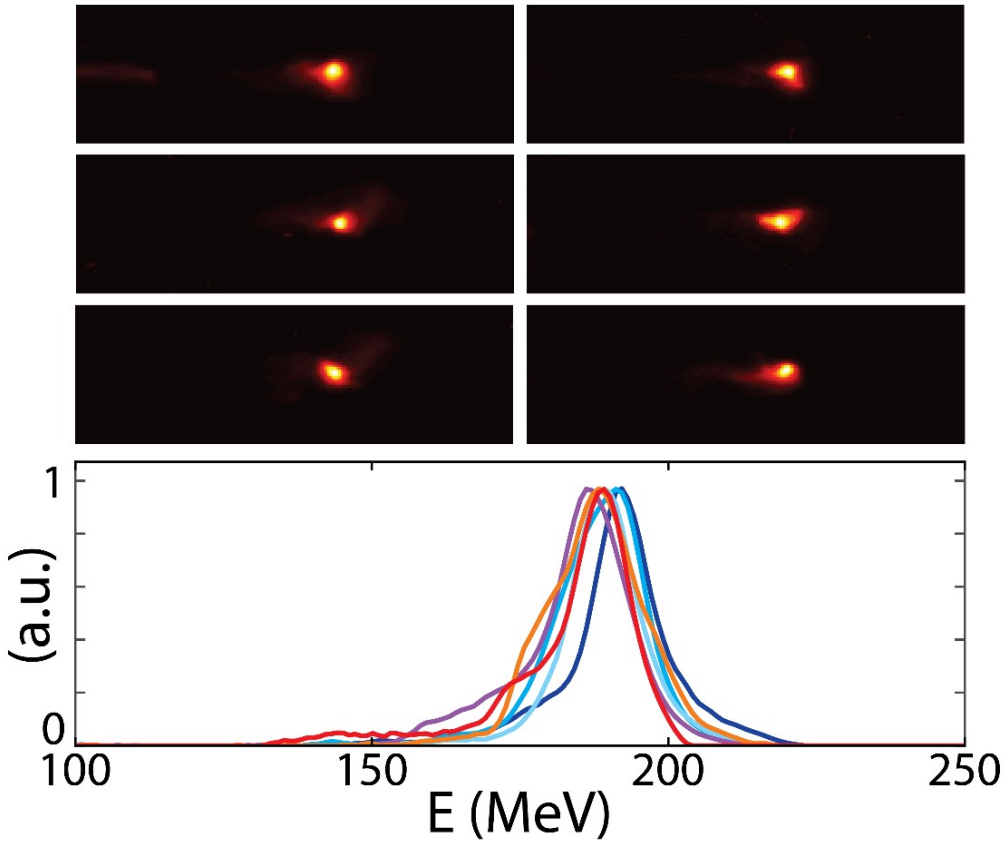
Results

Q= 17 pC

dE/E_{peak} = 8%

Divergence = 6 mrad

Exascale simulations informed the design of the first experimental validation of our concept (at LOA)



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And…

Stability shot by shot !

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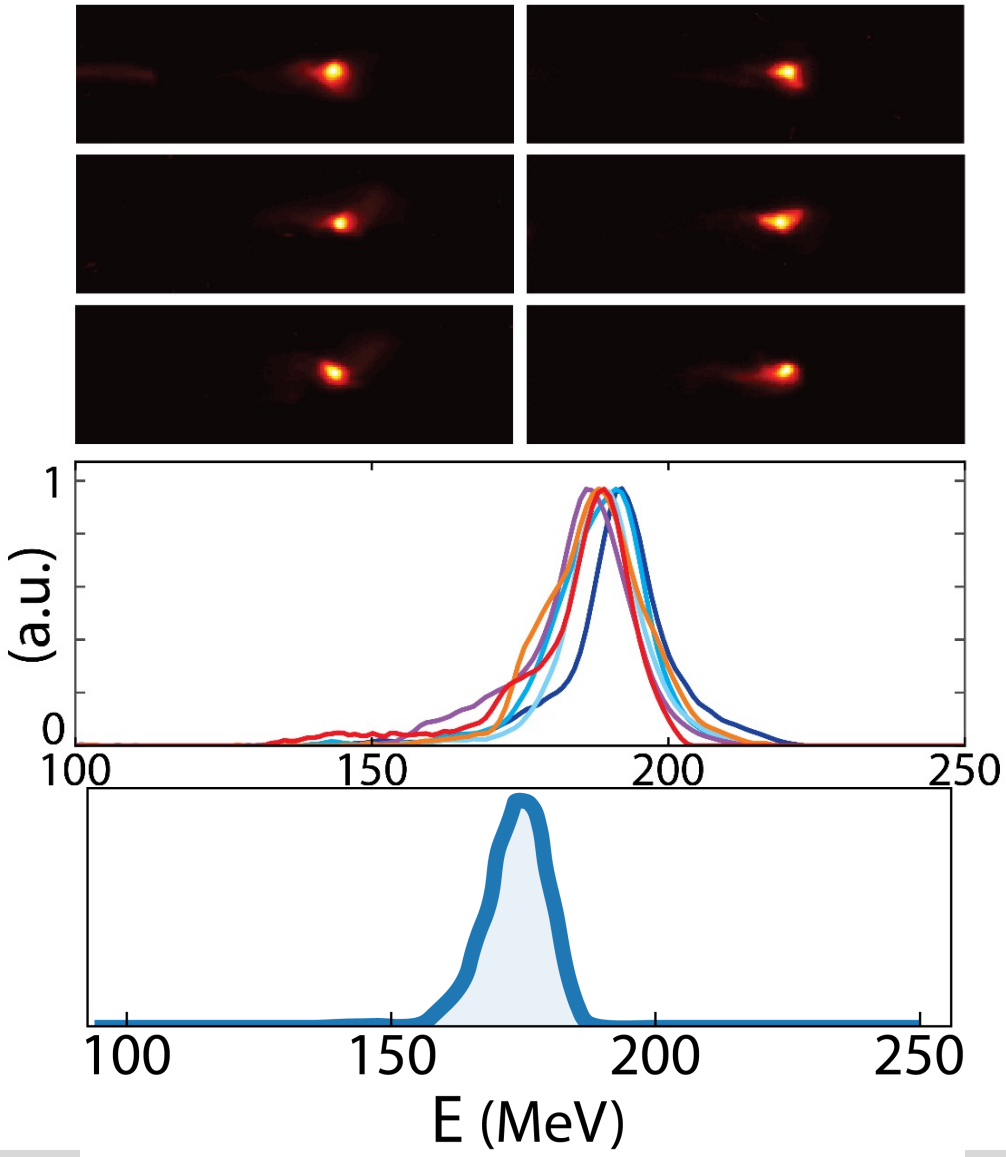


Results

Q= 17 pC

dE/E_{peak} = 8%

Divergence = 6 mrad

And…

Stability shot by shot !

Validated with simulations

Q= 26 pC

dE/E_{peak} = 9%

Divergence = 10 mrad

Exascale simulations informed the design of a second experimental validation of our concept (at LOA)

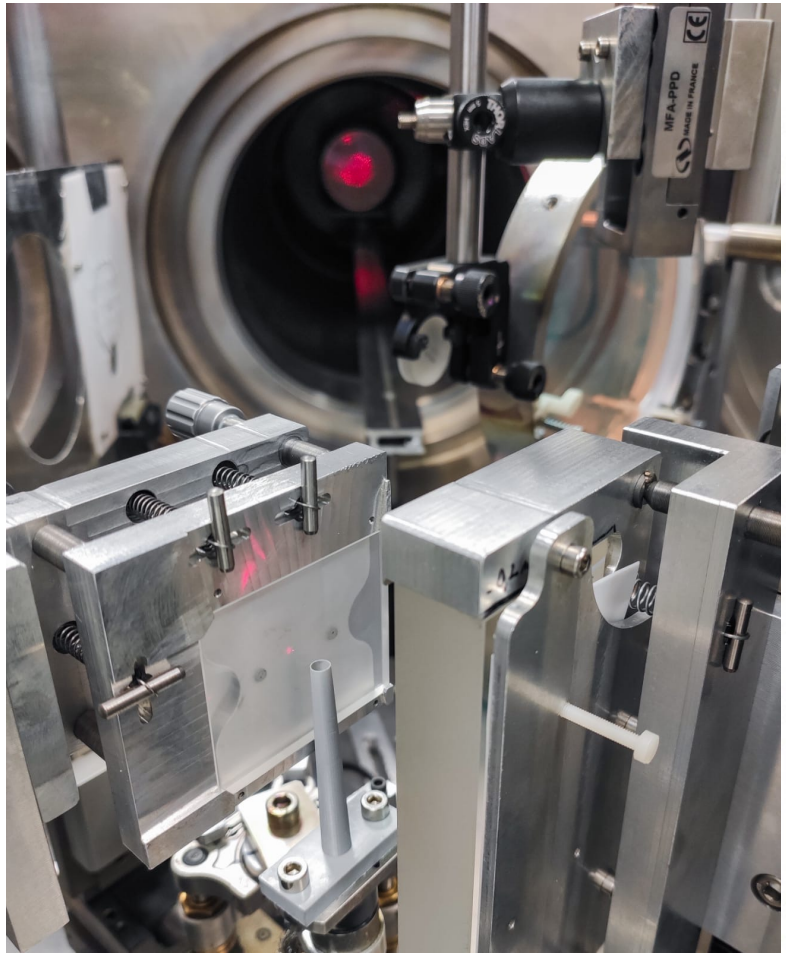
With Adrien Leblanc, UPX

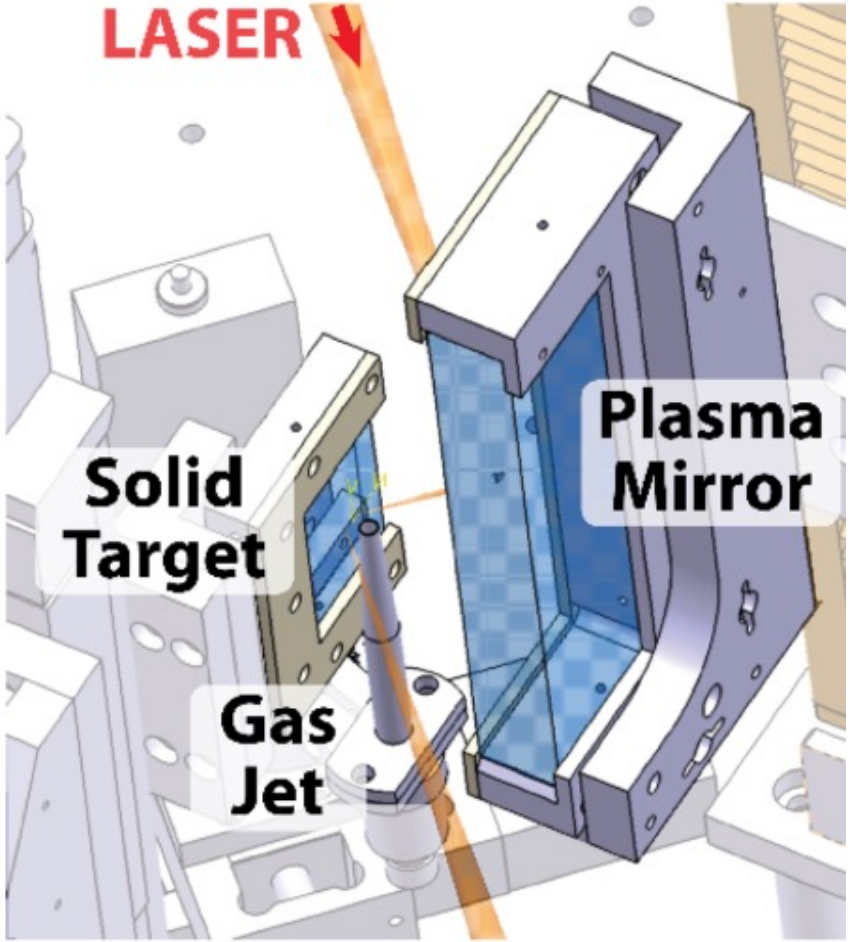
Laser parameters

E = 1.1 J

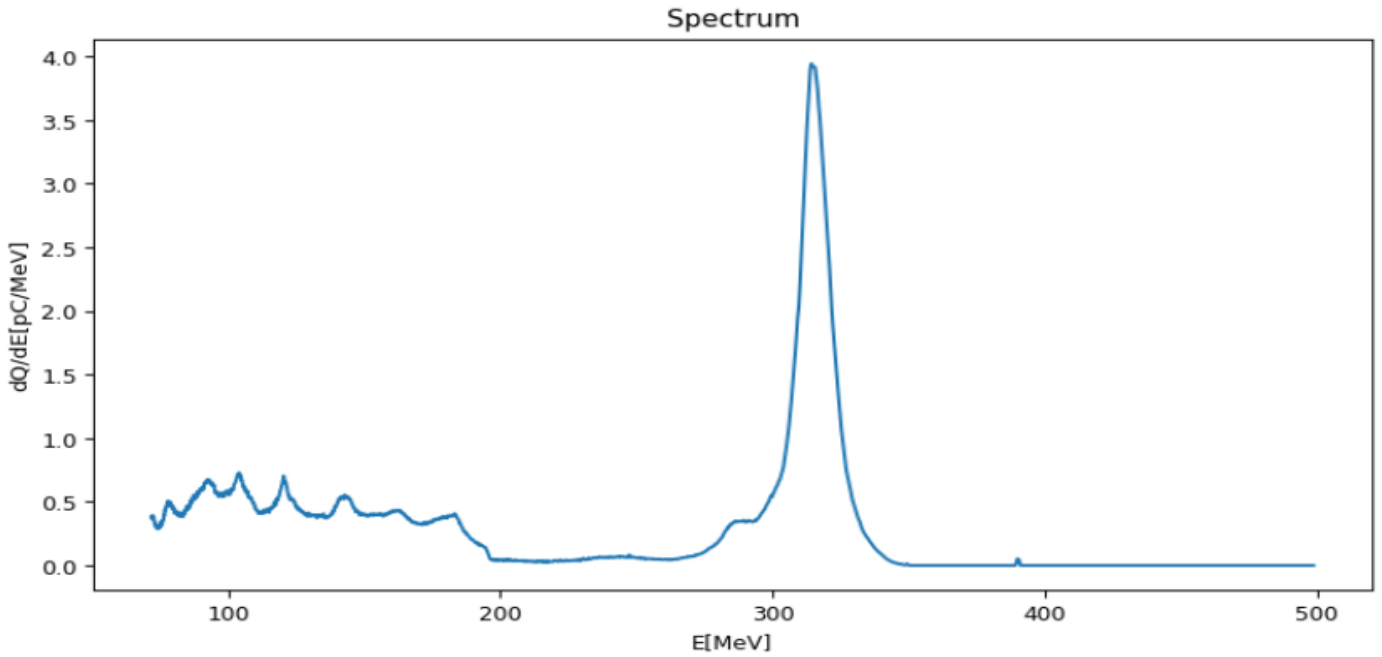
waist = 25 µm

P_{peak} = 40 TW





Exascale simulations informed the design of the first experimental validation of our concept (at LOA)



Results :

Q =111 pC

E_{peak} **=324 MeV**

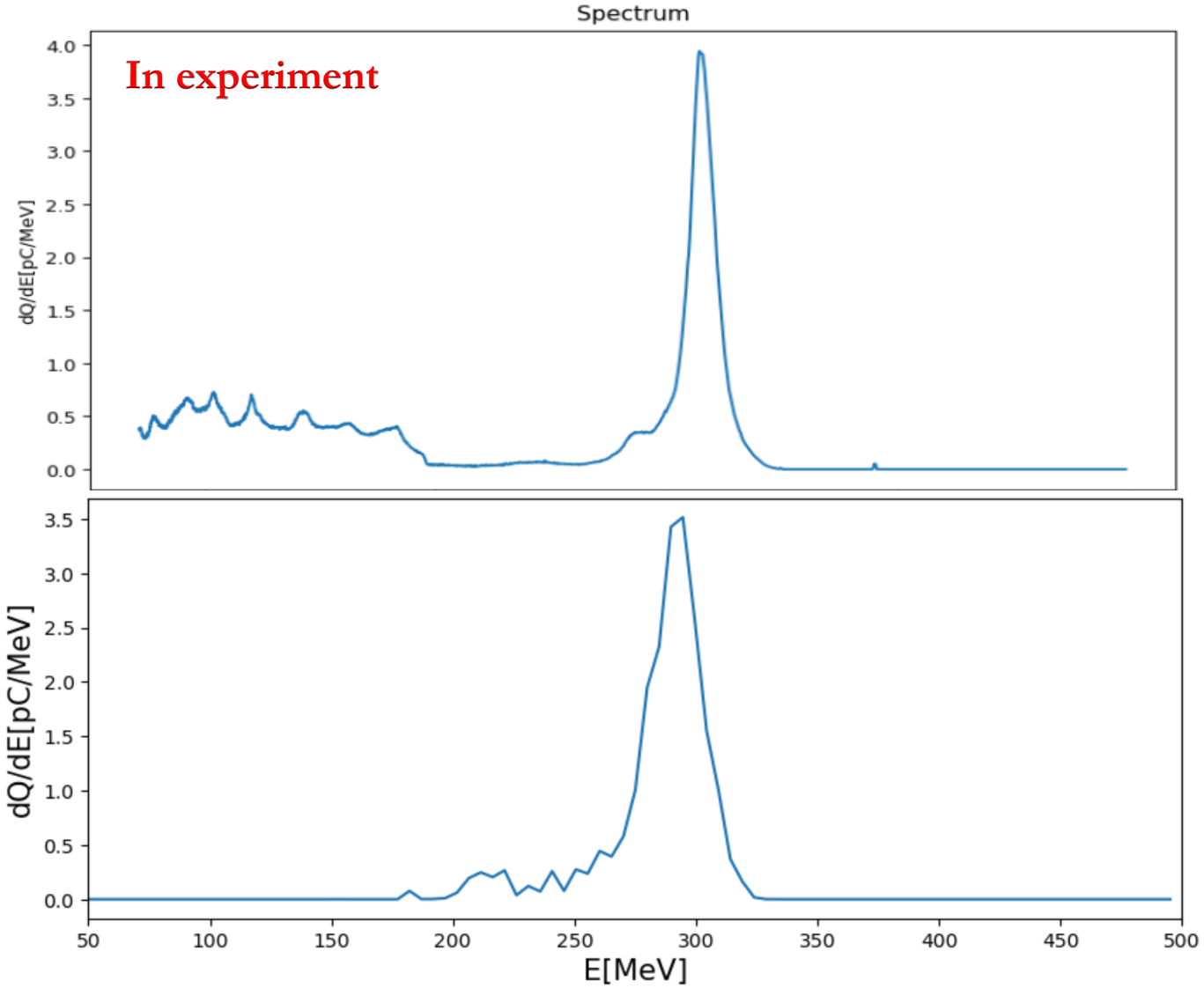
$\frac{dE}{E_{peak}} \sim 6.3\%$

$\Delta\vartheta \sim 4\ mrad$

A proof-of-concept of this technique !

- **Conversion efficiency is 2x better than the state of the art**

Exascale simulations informed the design of the first experimental validation of our concept (at LOA)



In experiment :

Q =111 pC

E_{peak} =324 MeV

$\frac{dE}{E_{peak}} \sim 6.3\%$

$\Delta\vartheta \sim 4\ mrad$

In Simulation :

Q =90 pC

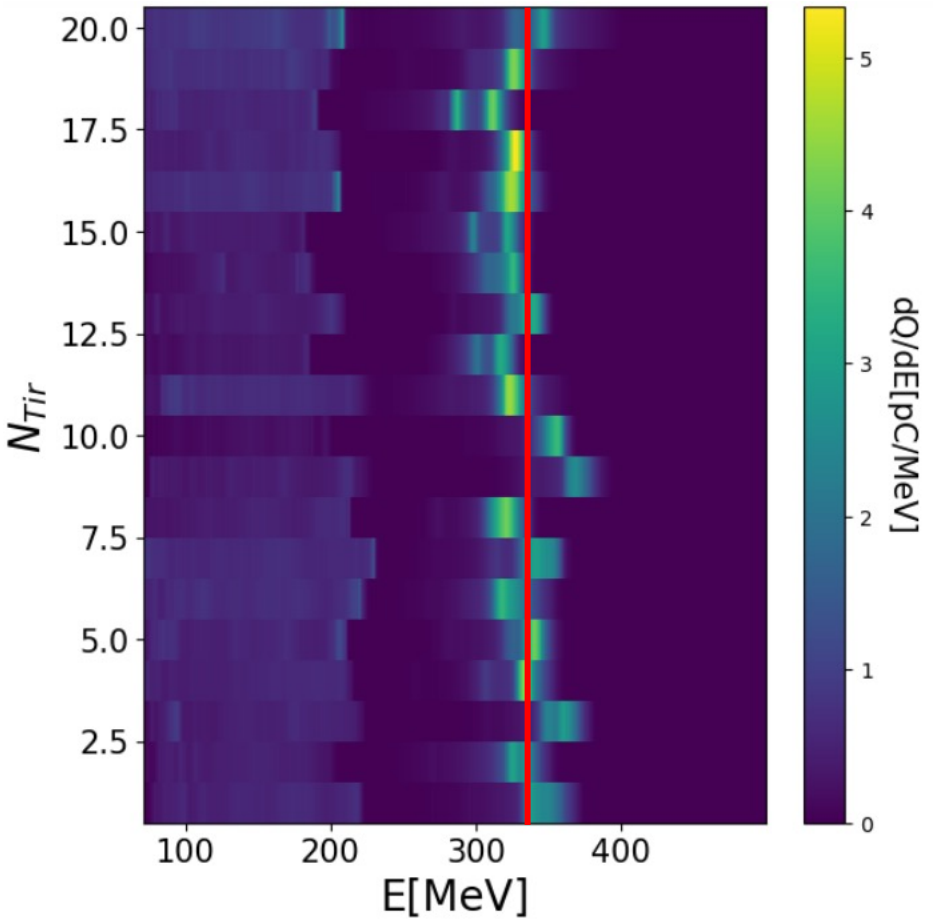
E_{peak} =300 MeV

$\frac{dE}{E_{peak}} \sim 5\%$

$\Delta\vartheta \sim 10\ mrad$

Exascale simulations informed the design of the first experimental validation of our concept (at LOA)

20 consecutives shots



Results :

$Q = 111 \mp 18$ pC

$E_{peak} = 324 \mp 15$ MeV

$\frac{dE}{E_{peak}} \sim 6.3 \mp 2.7\%$

$\Delta\vartheta \sim 4 \mp 0.3\ mrad$

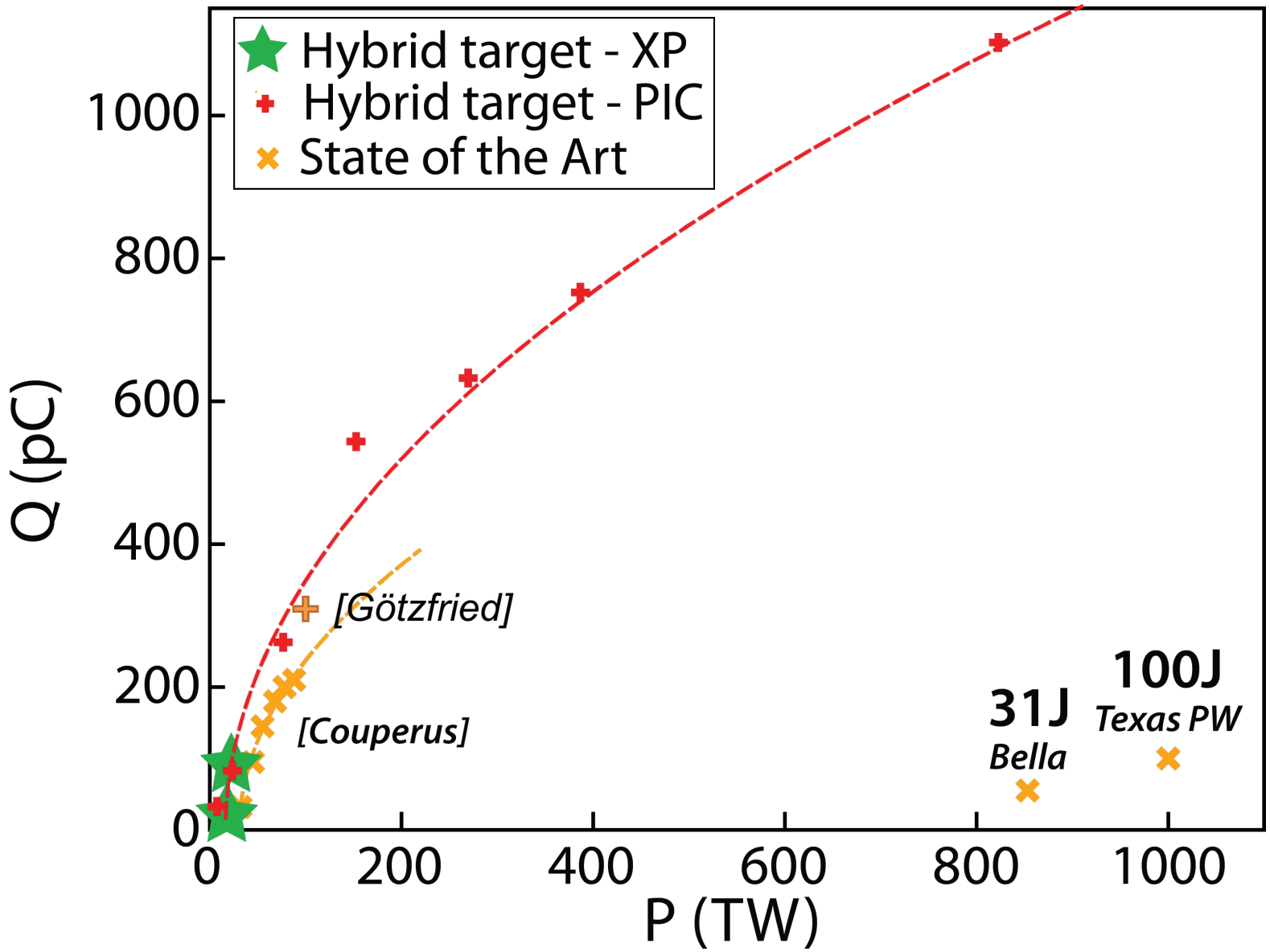
- A proof-of-concept of this technique !

… and stable !

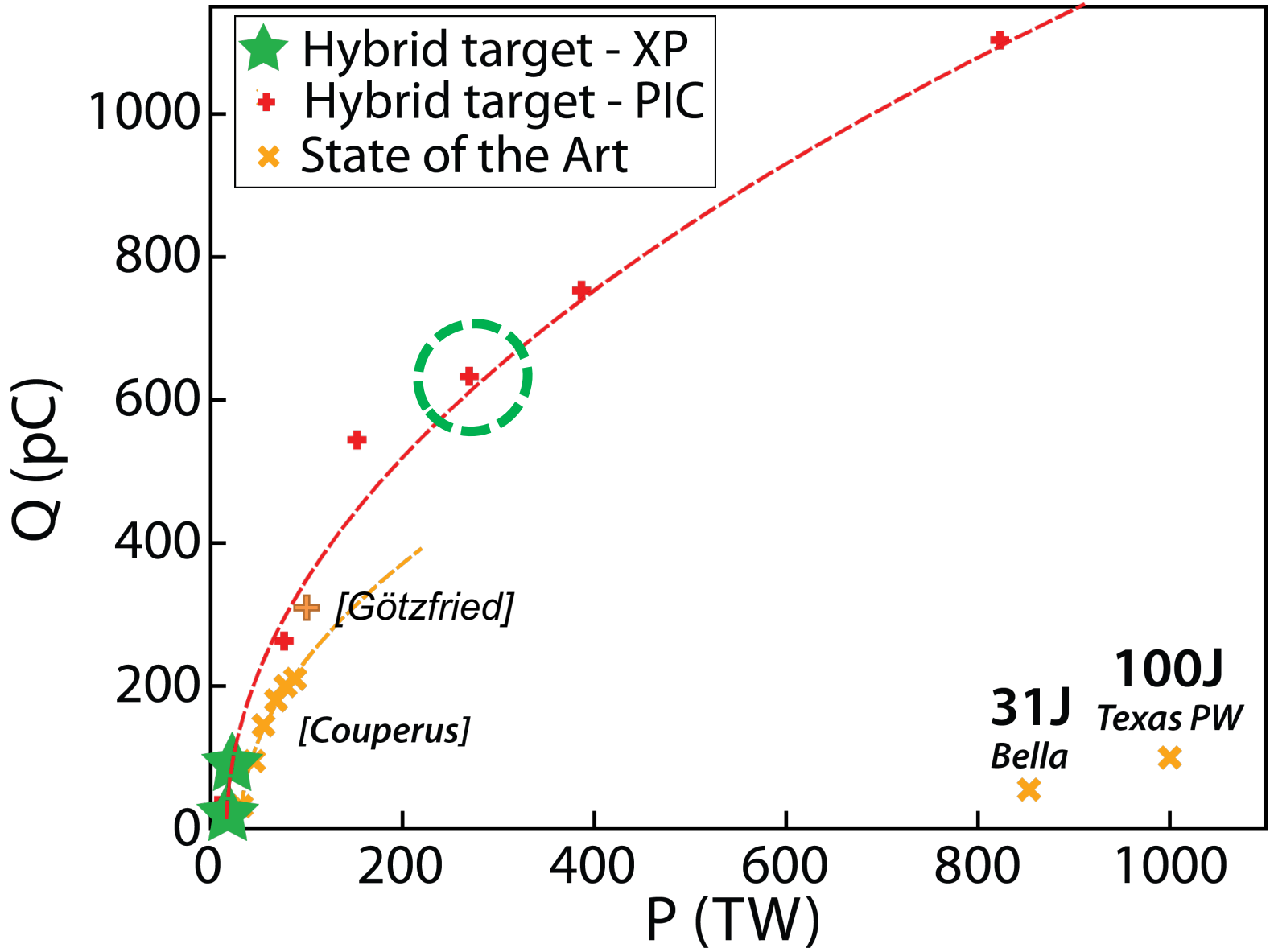
- The results are more than 2 times better than state-of-art in efficiency

What's next ?

What's next ?

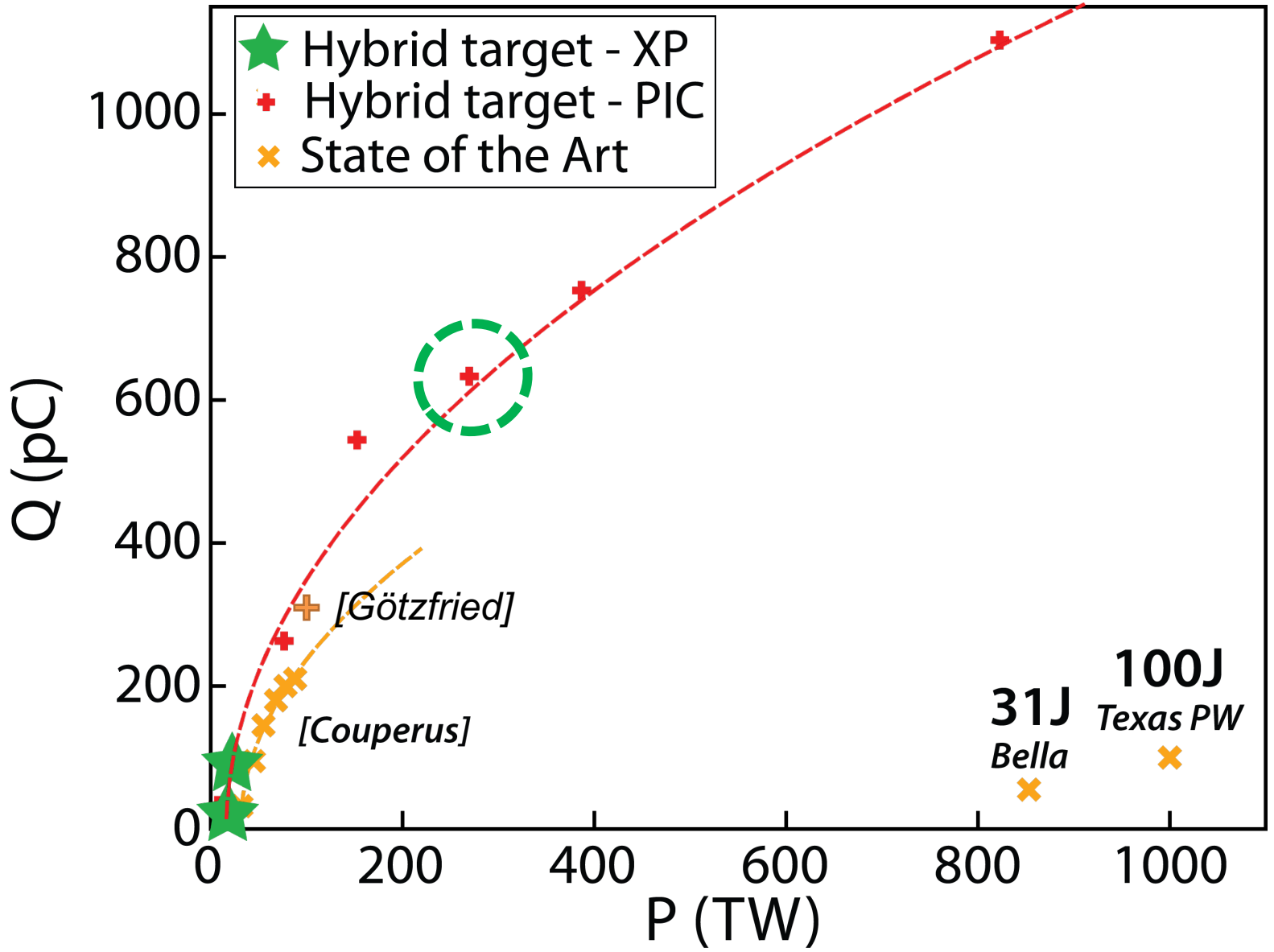

Hybrid target - XP
Hybrid target - PIC
State of the Art
Q (pC)
P (TW)
0
200
400
600
800
1000
[Götzfried]
[Couperus]
31J
Bella
100J
Texas PW

What's next ?



Next experimental campaign at apollon !

What's next ?



Next experimental campaign at apollon !

Preliminary results :

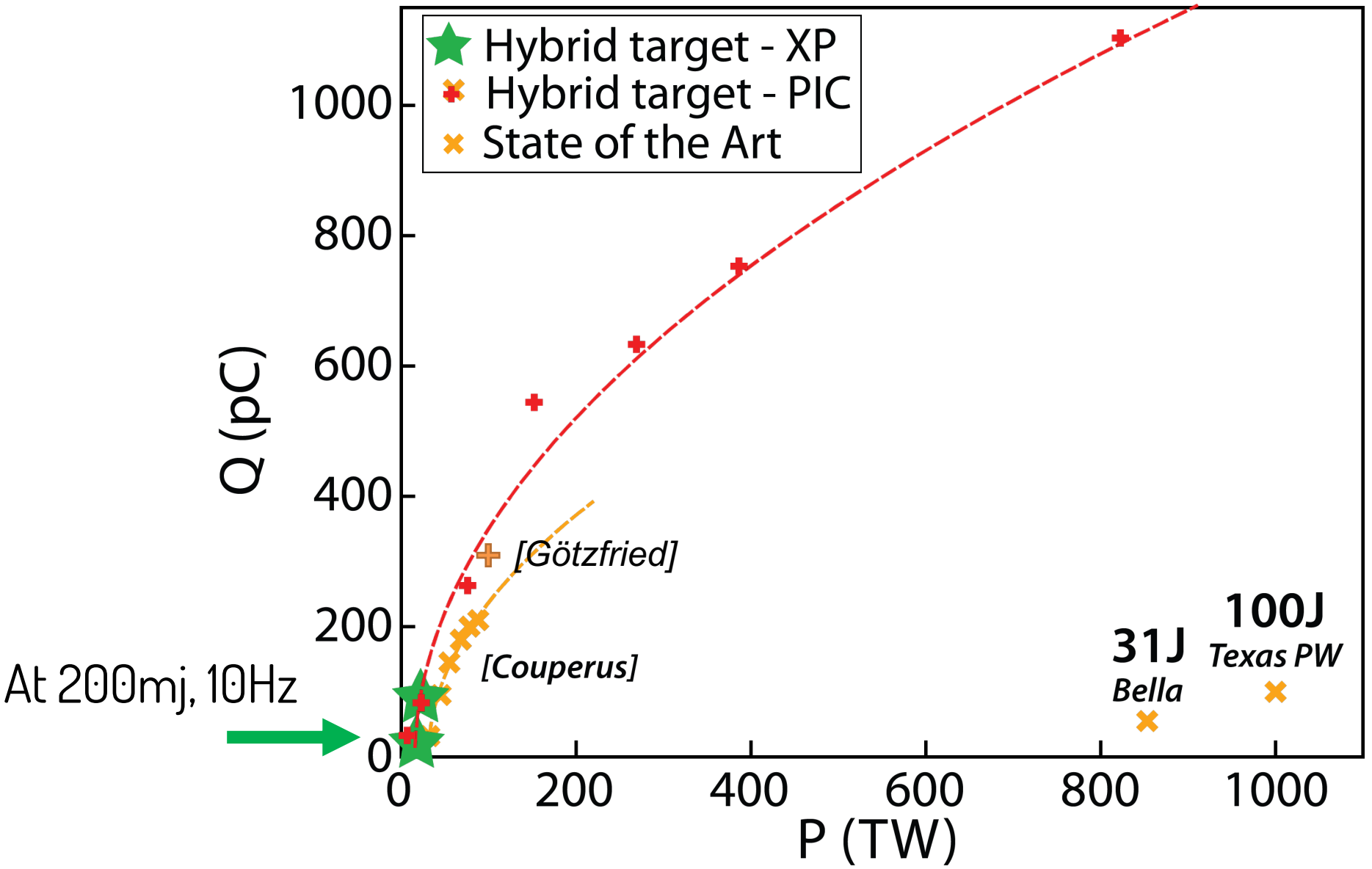
Q=600pC

E = 600 MeV

dE/E_{peak} = 5%

- **Promising for QED experiments !**

What's next ?



Next experimental campaign at LP3 at Marseille !

Preliminary results :

Q=30pC

E = 100 MeV

dE/E_{peak} = 30%

- **Promising for radiobiology and radiotherapy experiments!**

Conclusions and perspectives

- The Hybrid target is an ambitious scheme to numerically study and it is possible thanks to the WarpX P.I.C. code

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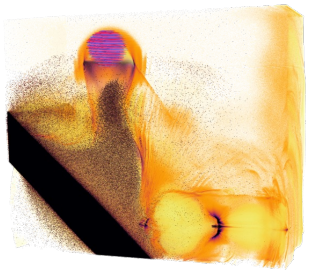
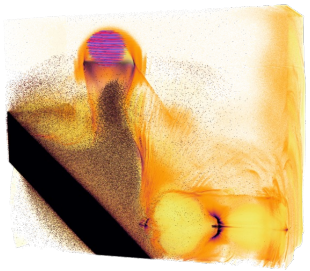


- The Hybrid Target provide high charge beams at high energy but with also high quality !

Conclusions and perspectives

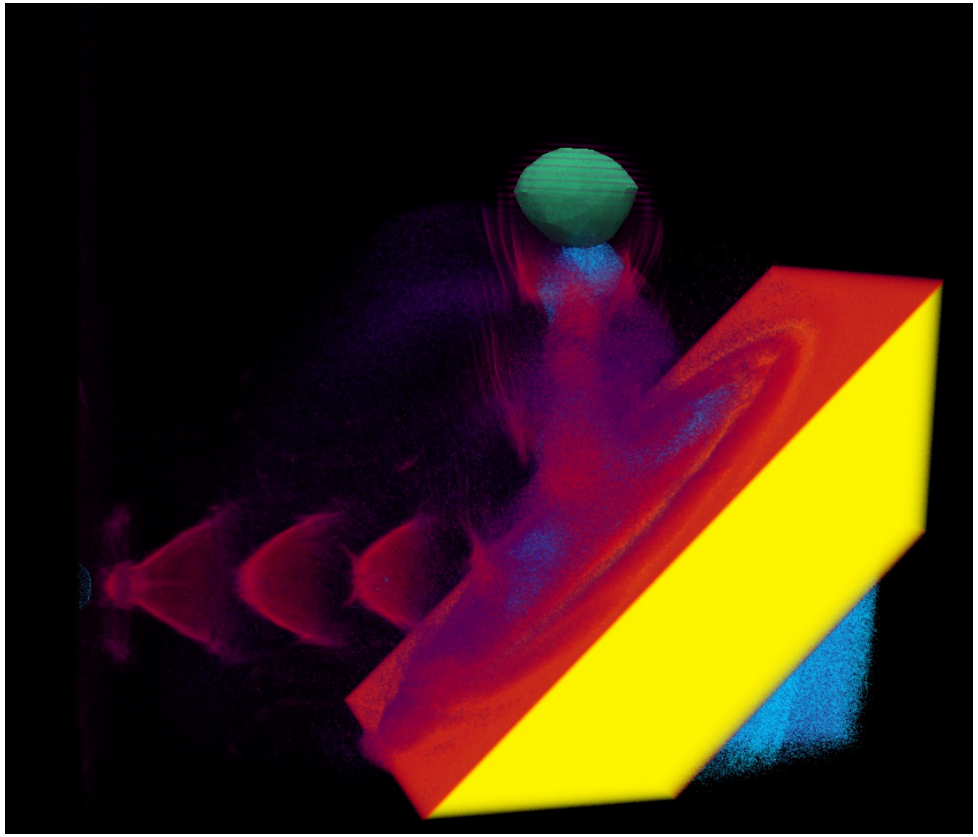
- The Hybrid target is an ambitious scheme to numerically study and it is possible thanks to the WarpX P.I.C. code



- The Hybrid Target provide high charge beams at high energy but with also high quality !

- This promising technique could have bigger impact on PW class laser and at High rate with lower energy

A novel laser-driven electron scheme based on a plasma-mirror injector



Luca Fedeli, Axel Huebl, France Boillod-Cerneux, Thomas Clark, Kevin Gott, Conrad Hillairet, Stephan Jaure, Adrien Leblanc, Rémi Lehe, Andrew Myers, Christelle Piechurski, Mitsuhisa Sato, Neil Zaim, Weiqun Zhang, Jean-Luc Vay, Henri Vincenti

The End