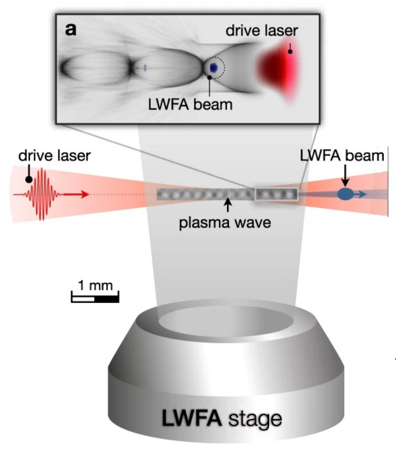
Modeling a Novel Laser-Driven Electron Acceleration Scheme: Particle-In-Cell Simulations at the Exascale

L. Fedeli[1], A. Huebl[2], F. Boillod-Cerneux[1], T. Clark[1], K. Gott[2], C. Hillairet[3], S. Jaure[4], A. Leblanc [5], R. Lehe[2], A. Myers[2], C. Piechurski[6], M. Sato[7], N. Zaïm[1], W. Zhang[2], J.-L. Vay[2] , and H. Vincenti[1]

1) CEA Saclay, France 2) Lawrence Berkeley National Laboratory, USA 3) Arm, France 4) ATOS, France 5) ENSTA Paris, CNRS, Ecole polytechnique, France 6) GENCI, France 7) RIKEN, Japan

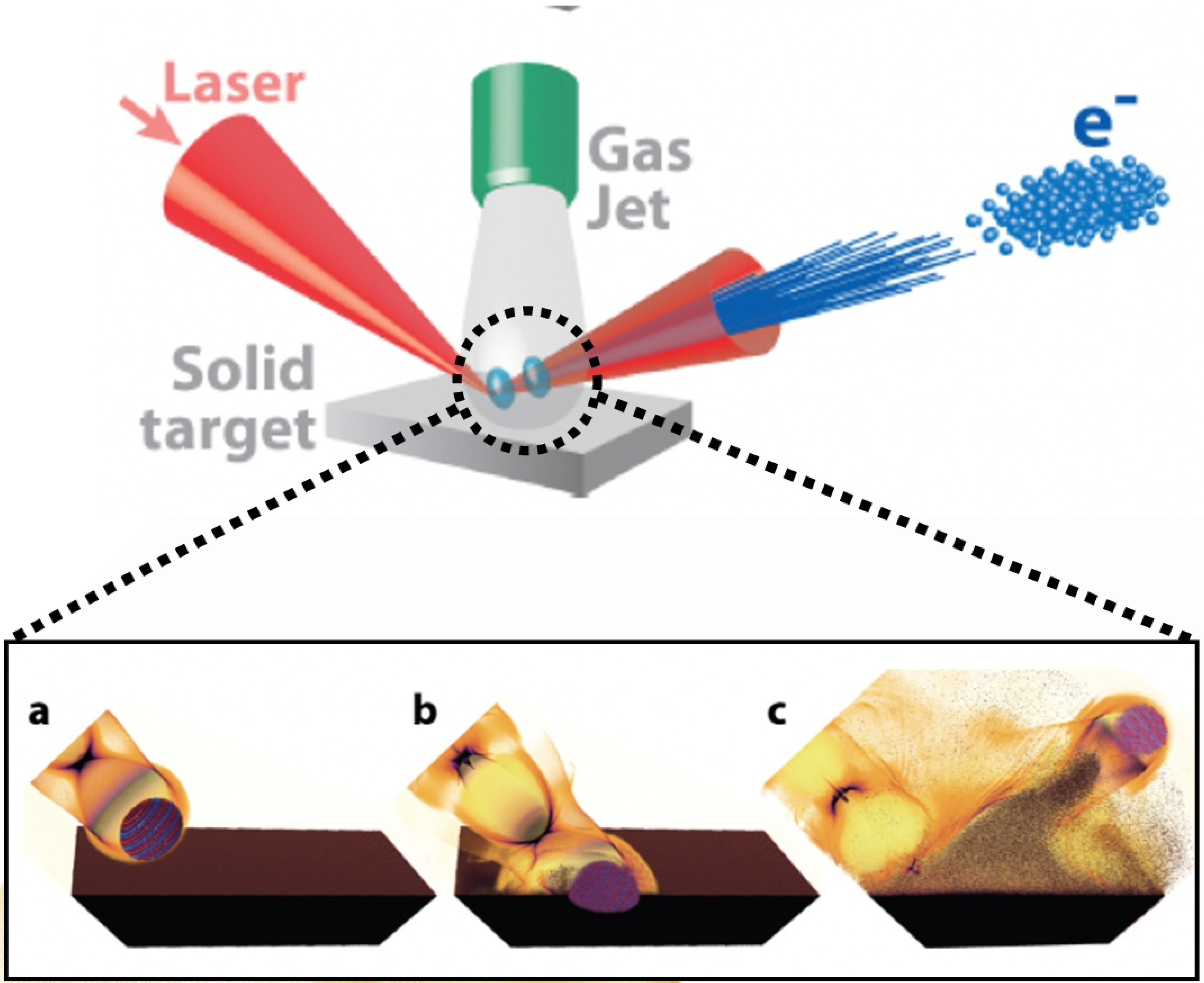
Laser Wakefield Acceleration (LWFA) of e- is a promising technique but...



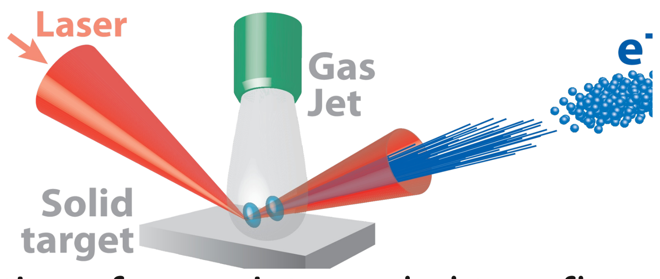
From T.Kurz et al. Nat.Comm. 12, 2895 (2021). CC BY 4.0

Intense femtosecond lasers focused on low-density gas jets can **accelerate ultra-short electron bunches** up to very high energies (from 100s of MeV to several GeV) **over a few mm or a few cm.** However, with conventional LWFA techniques, it is hard to accelerate more than a few 10s of picoCoulomb of charge at high energy and with high quality, severely hindering potential applications..

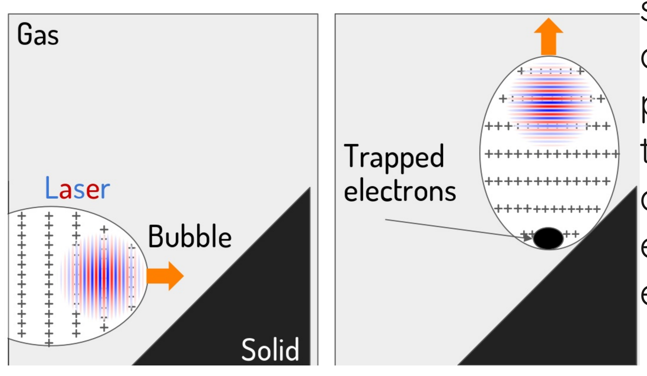
...accelerating high quality and high charge e- bunches is difficult



We propose a novel injector concept to accelerate more charge



In LWFA, injecting a high charge from a low-density gas jet is challenging. To address this issue, we have devised a **novel injector consisting of a gas jet coupled to a flat solid target.** By interacting with the high-density target, the **laser should be able to extract a substantial amount of charge.** The laser is subsequently reflected and propagates in the gas jet, as in conventional LFWA setups, generating a density perturbation that traps and accelerates the electrons up to high energies.

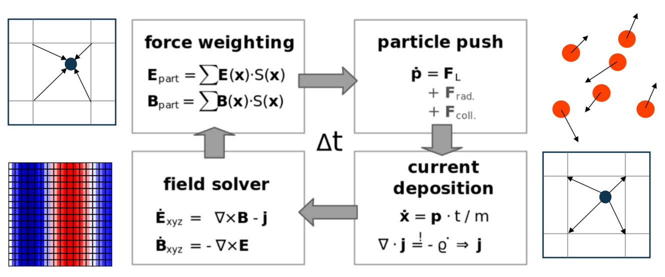


We validated this concept with numerical simulations & experiments

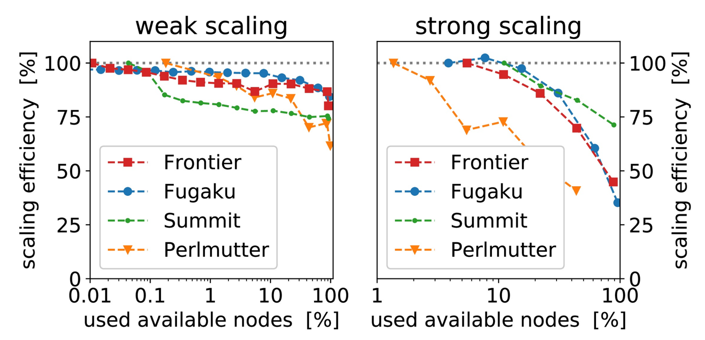
WarpX: a Particle-in-Cell code for the exascale era

Gordon Bell prize winner @ SC22

WarpX is an **open-source Particle-In-Cell** code conceived to address the challenge of **simulating kinetic plasmas at the exascale.**



WarpX supports mesh-refinement, advanced solvers, dynamic load balancing, highly scalable I/O routines, and several additional physics modules. WarpX is well-tested to simulate ultra-intense laser-plasma interaction scenarios, including LWFA, and is routinely used on the top supercomputers in the world. A scientific work describing the technical innovations implemented in WarpX was awarded the **Gordon Bell Prize in 2022.**

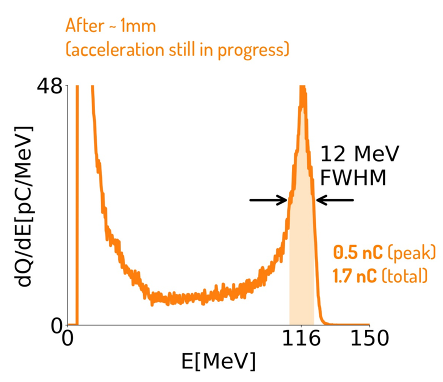


WarpX exhibits an **excellent weak scaling** on several of the top supercomputers in the world, and it can also be strong-scaled by roughly one order of magnitude. We performed scalability tests using uniform plasma simulations on the following machines: **Frontier** (OLCF, USA, #1 in the top500), **Fugaku** (Riken, JP, #2 in the top500), **Summit** (OLCF, USA, #5 in the top500), and **Perlmutter** (NERSC, USA, #8 in the top500).

WarpX is built on top of the **open-source AMReX library**, which provides a **performance portability** layer

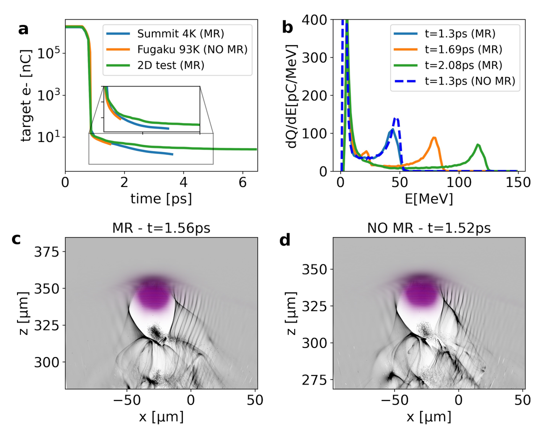
```
amrex::ParallelFor( n_particles,
  [=] AMREX_GPU_DEVICE (long i) {
    UpdatePosition( x[i], y[i], z[i],
       ux[i], uy[i], uz[i], dt );
});
```

Massively parallel Particle-In-Cell simulations validate our concept



Mesh-refined, massively parallel simulations show that with a PW-class laser **a substantial amount of charge can be extracted from the solid part of the target**, much more than what would be accelerated with just the gas jet.. The extracted charge is then accelerated by LWFA in the gas. Electron injection is highly localized, leading to **peaked electron spectra with an energy spread below 10% and an energy above 100 MeV**. The simulation was carried out on **4096 nodes on the Summit supercomputer**, using two MR levels: a first level with 3840 × 1920 × 3840 grid nodes and a second level with 7680 × 2151 × 5120 grid nodes.

We validated Mesh refinement at scale in an EM Particle-In-Cell code

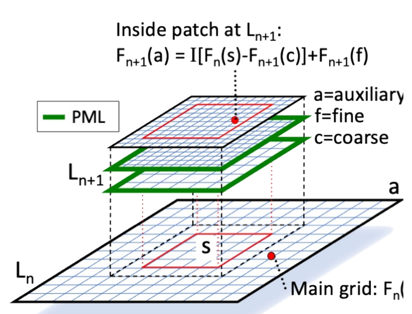


We validated the **mesh refinement feature** through a comparison with a simulation performed on 93K Fugaku nodes without mesh refinement and at an intermediate resolution between the highest and lowest used in the MR simulation.

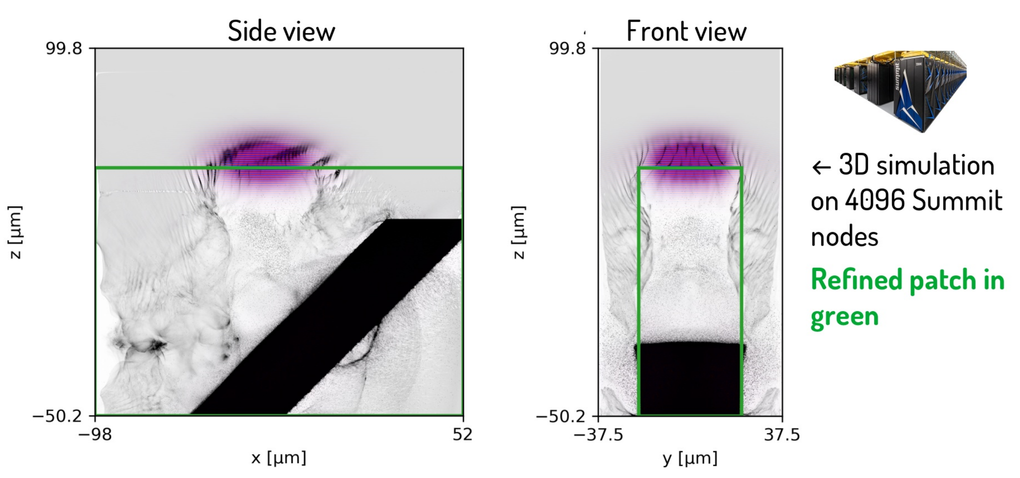
Fig. a-b show that the injected charge and the e⁻ spectra agree well with or without mesh refinement. Fig. c-d, displaying snapshots of the laser field and plasma density after reflection on the solid target, also shows **a good agreement between the two cases.**

Mesh refinement in electromagnetic Particle-In-Cell codes

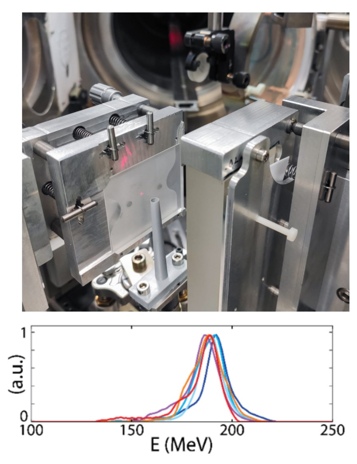
Mesh refinement is among the most advanced features of the WarpX code, which is indeed the only electromagnetic Particle-In-Cell code providing this capability. The implementation of mesh refinement requires the use of absorbing layers to deal with the spurious reflection of electromagnetic waves at the boundary.



WarpX allows defining a rectangular region where a resolution higher than that of the main grid is used. The high-resolution region can be removed as soon as it is not required anymore, leading to substantial speedups.



We validated our concept with a proof-of principle experiment



In 2022 we validated our concept with **proof-of-principle experiments** carried out at the **10 TW-class LOA laser facility (France)**. We observed a **2.5x increase of the conversion efficiency** of laser energy into electron energy with respect to the best result obtained at that facility with more conventional LWFA setups.

References

[1] L.Fedeli et al. (2022). "Pushing the frontier in the design of laser-based electron accelerators with groundbreaking mesh-refined particle-in-cell simulations on exascale-class supercomputers." In 2022 SC22: International Conference for High Performance Computing, Networking, Storage and Analysis (SC) (pp. 25-36). IEEE Computer Society.

[2] A.Myers et al. (2021). "Porting WarpX to GPU-accelerated platforms". Parallel Computing, 108, 102833.

[3] J.-L. Vay et al. (2004). "Application of adaptive mesh refinement to particle-in-cell simulations of plasmas and beams". Physics of Plasmas, 11(5), 2928-2934

[4] W. Zhang et al. (2019). "AMReX: a framework for block-structured adaptive mesh refinement". Journal of Open Source Software, 4(37), 1370-1370.

[5] WarpX github repository: https://ecp-warpx.github.io/