Next Generation Computational Tools for the Modeling and Design of Particle Accelerators at Exascale

EXASCALE COMPUTING PROJECT

Axel Huebl

Lawrence Berkeley National Laboratory

On behalf of the BLAST team (lead: Jean-Luc Vay @ LBNL)
LBNL, LLNL, SLAC, CEA, DESY, Modern Electron, CERN

Invited Oral - TUYE2
Computing and Data Science for Accelerator Systems

North American Particle Accelerator Conference (NAPAC22)

location: Albuquerque, NM, USA
August 9th, 2022

CAMPA Consortium for Advanced Modeling of Particle Accelerators

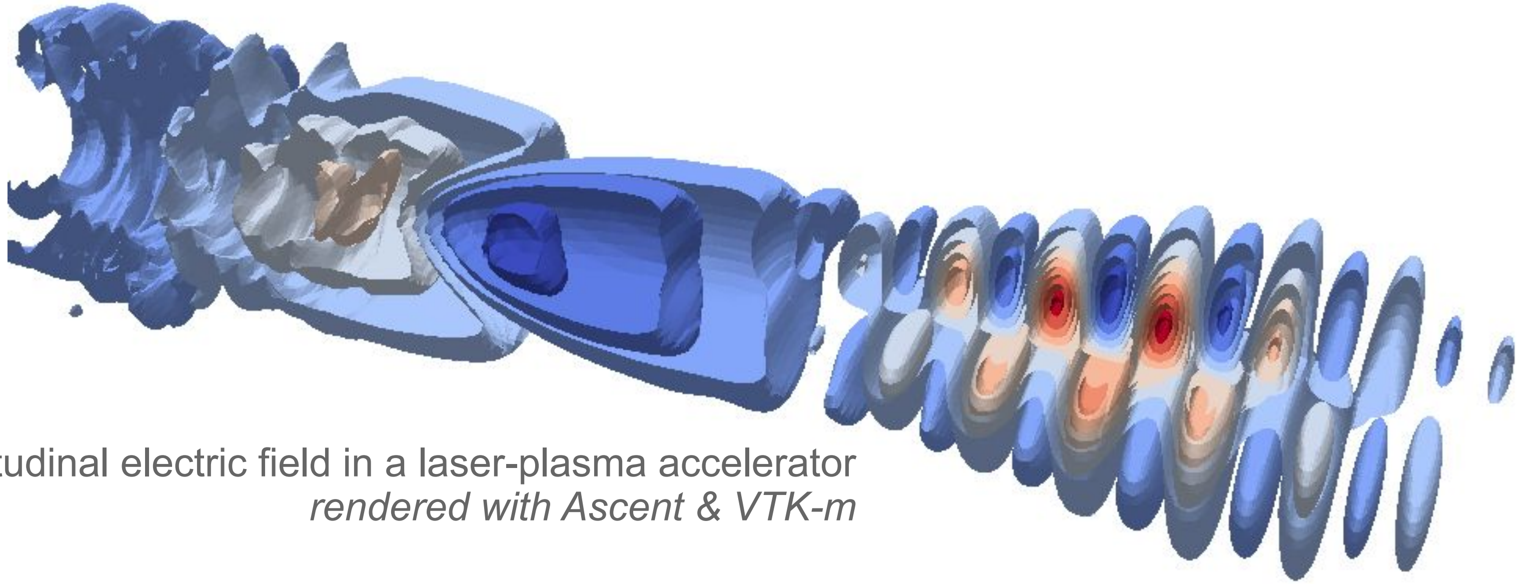
NNSA National Nuclear Security Administration

BERKELEY LAB

ATAP ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

U.S. DEPARTMENT OF ENERGY | Office of Science

Funding Support



WarpX: longitudinal electric field in a laser-plasma accelerator
rendered with Ascent & VTK-m

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This research was supported by the **Exascale Computing Project** (17-SC-20-SC), a joint project of the U.S. Department of Energy's Office of Science and National Nuclear Security Administration, responsible for delivering a capable exascale ecosystem, including software, applications, and hardware technology, to support the nation's exascale computing imperative. This work was supported by the **Laboratory Directed Research and Development Program** of Lawrence Berkeley National Laboratory under U.S. Department of Energy Contract No. DE-AC02-05CH11231. This research used resources of the **Oak Ridge Leadership Computing Facility**, which is a DOE Office of Science User Facility supported under Contract DE-AC05-00OR22725, the **National Energy Research Scientific Computing Center** (NERSC), a U.S. Department of Energy Office of Science User Facility located at Lawrence Berkeley National Laboratory, operated under Contract No. DE-AC02-05CH11231 using NERSC award ASCR-ERCAP0022112. This work used computational resources of the supercomputer Fugaku provided by **RIKEN** through the HPCI System Research Project (Project ID: ra010013)

- BLAST: Beam pLasma Accelerator Simulation Toolkit
- IO, Standardization & Open Development
- HPC: The Exascale Computing Project and Beyond

Multidisciplinary, Multi-Institutional Contributor Team

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NNSA

ECP

BERKELEY LAB

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Ji Qiang
Ryan Sandberg
Olga Shapoval
Yinjian Zhao
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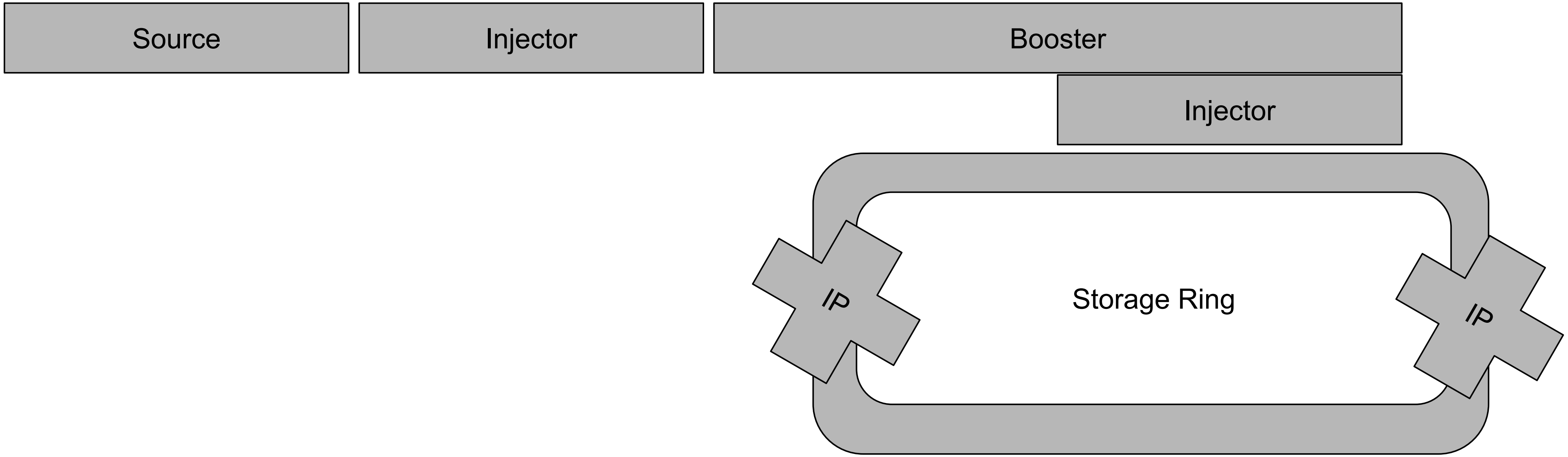
Intense Computing
Phil Miller

Simulation of Beam Sources & Dynamics Requires Different Types of PIC Codes

Imagine a future, ***hybrid* particle accelerator**, e.g., with conventional and plasma elements.



Goal
Start-to-end modeling in an open software ecosystem.

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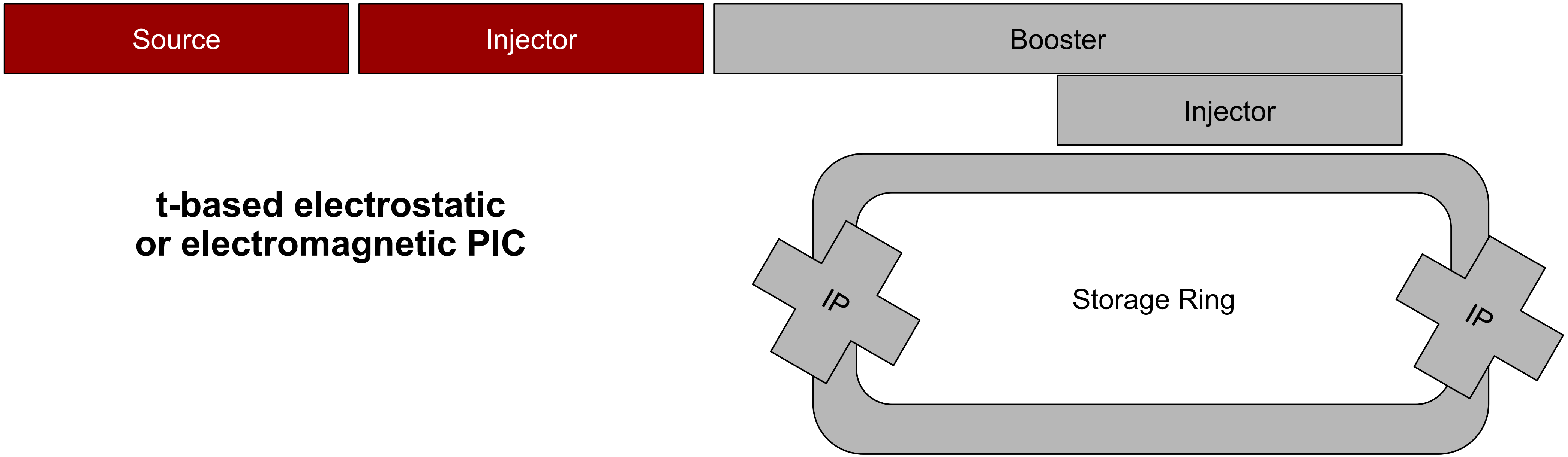

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EXASCALE COMPUTING PROJECT

SciDAC
Scientific Discovery through Advanced Computing

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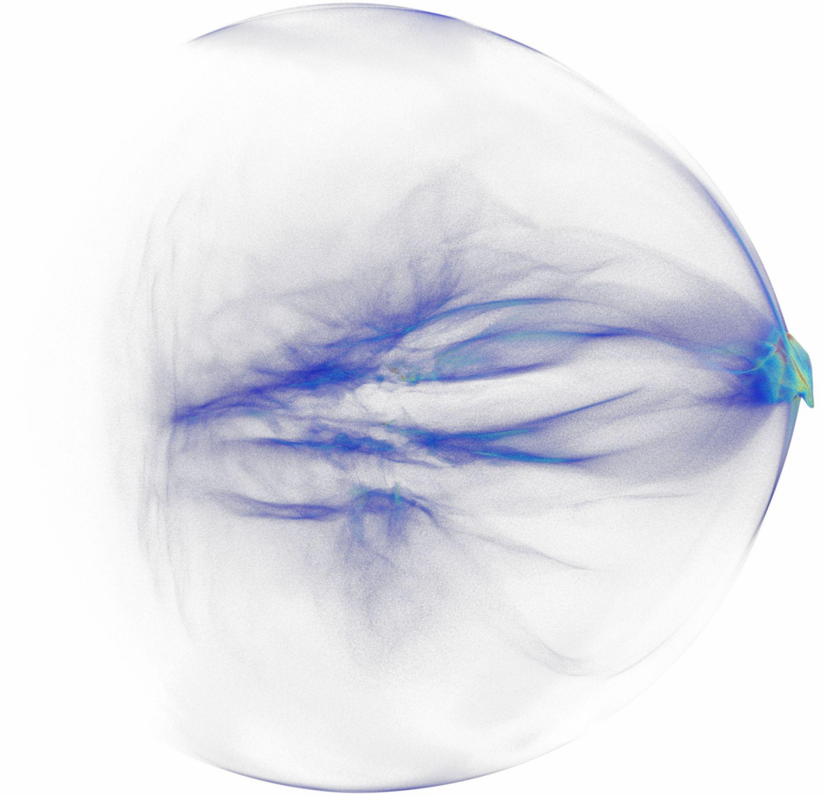
Imagine a future, ***hybrid* particle accelerator**, e.g., with conventional and plasma elements.

(S)RF Gun | LPA/LPI

Source | Injector | Booster

t-based electrostatic or electromagnetic PIC



3D visualization of the plasma proton density during the acceleration process of a few-fs, 1.15nC beam
Hilz, Ostermayr, Huebl et al.; Nat. Comm. **9**.432, 2018

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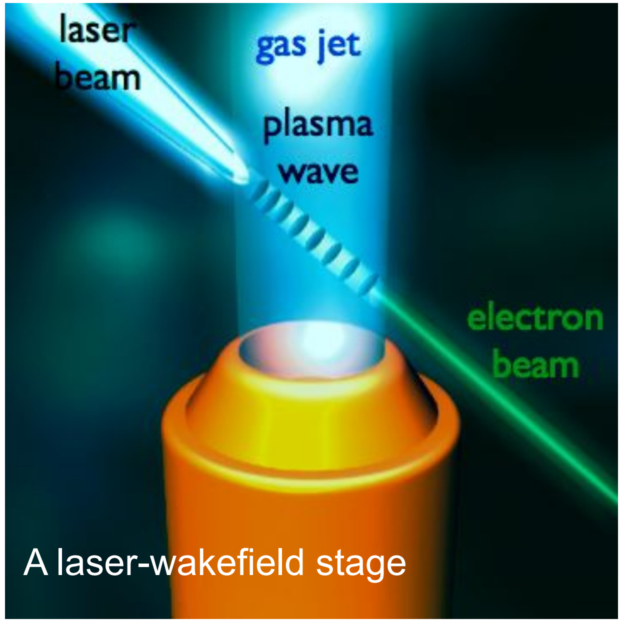

A laser-wakefield stage

Quasistatic PIC
separates the timescale for plasma wakefield and beam evolution

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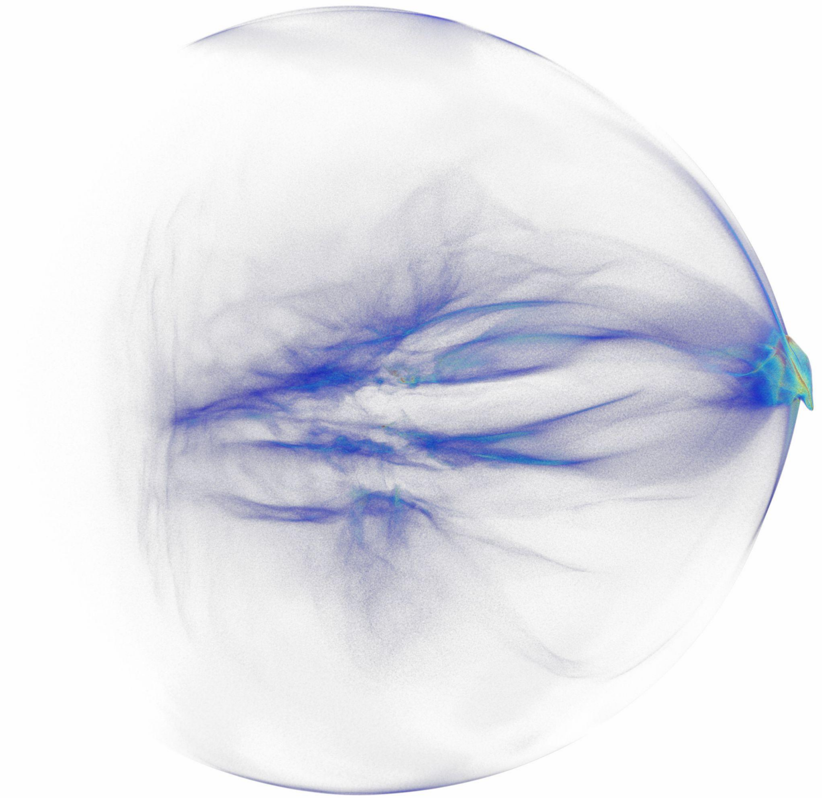

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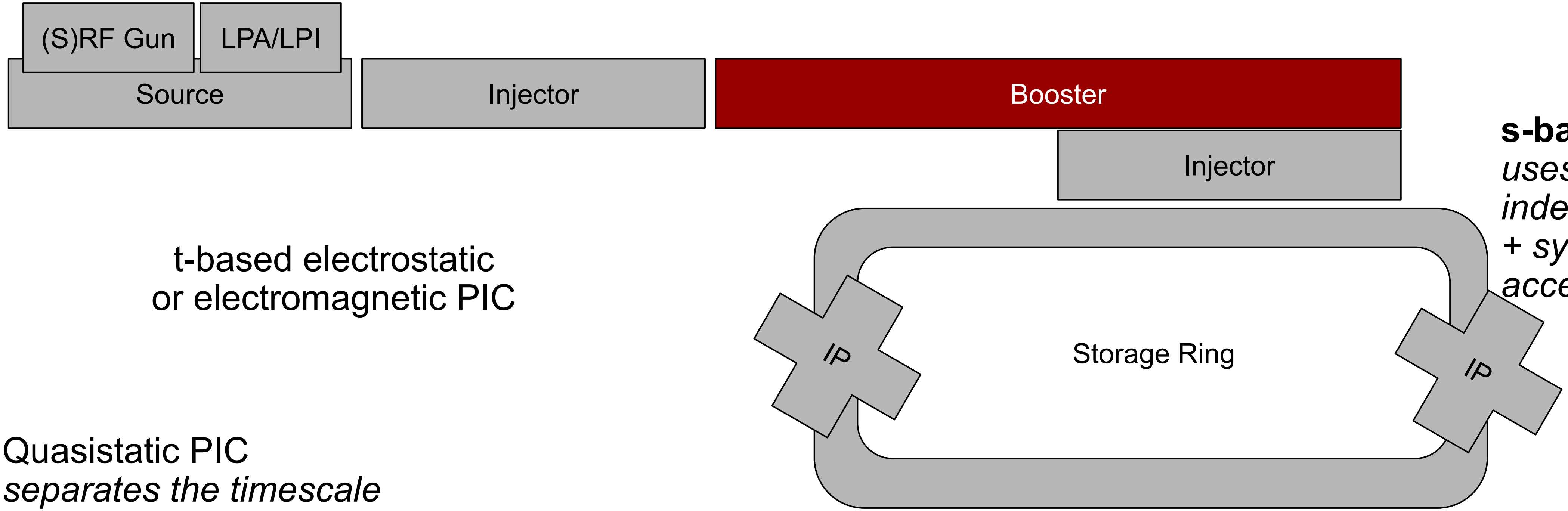

s-based PIC
uses s instead of t as independent variable + symplectic maps for accelerator elements

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separates the timescale for plasma wakefield and beam evolution

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Source

Injector

Plasma Stage | Plasma Stage
Booster
Injector

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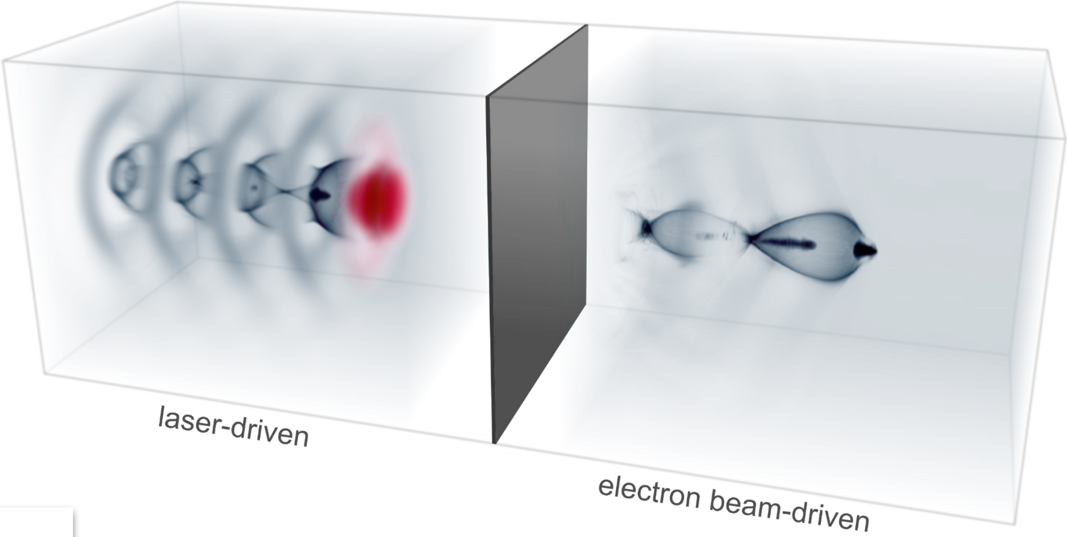

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Left: Laser-driven wakefield accelerator (LWFA) stage with the drive laser propagating to the right shown in red; right: plasma wakefield accelerator (PWFA) driven by the electron beam from the LWFA stage (figure credits: Thomas Heinemann/Strathclyde and Alberto Martinez de la Ossa/DESY). T. Kurz, T. Heinemann, et al. Nat. Comm. **12**.2895 (2021)

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SciDAC Scientific Discovery through Advanced Computing

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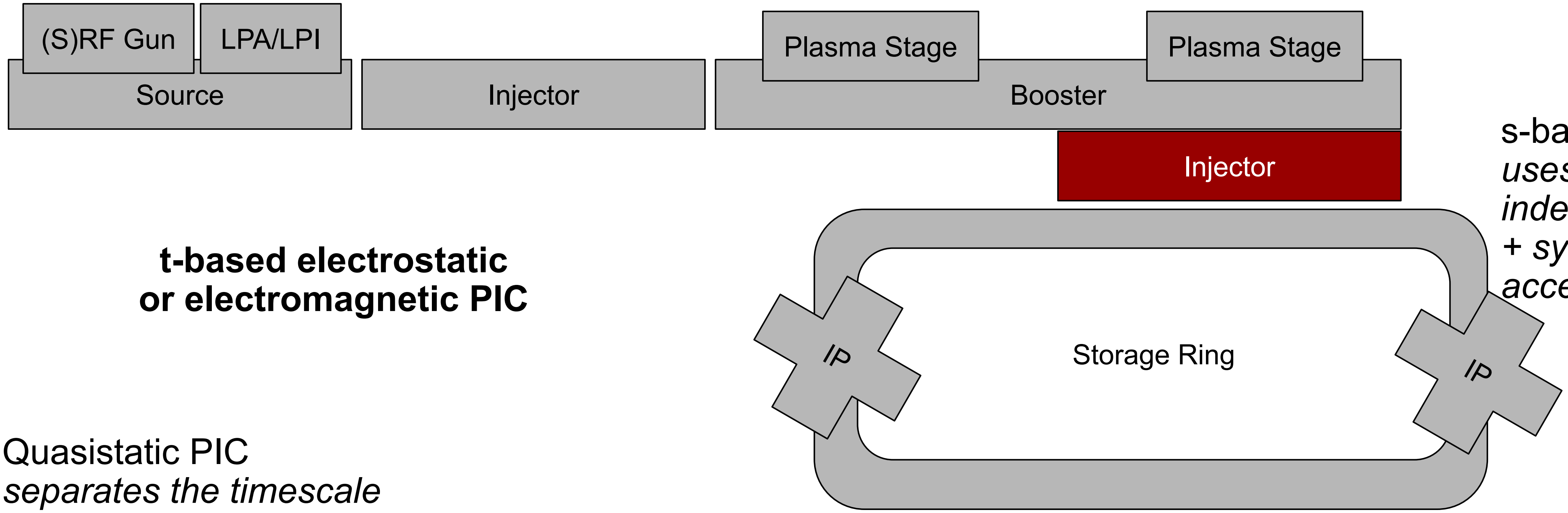

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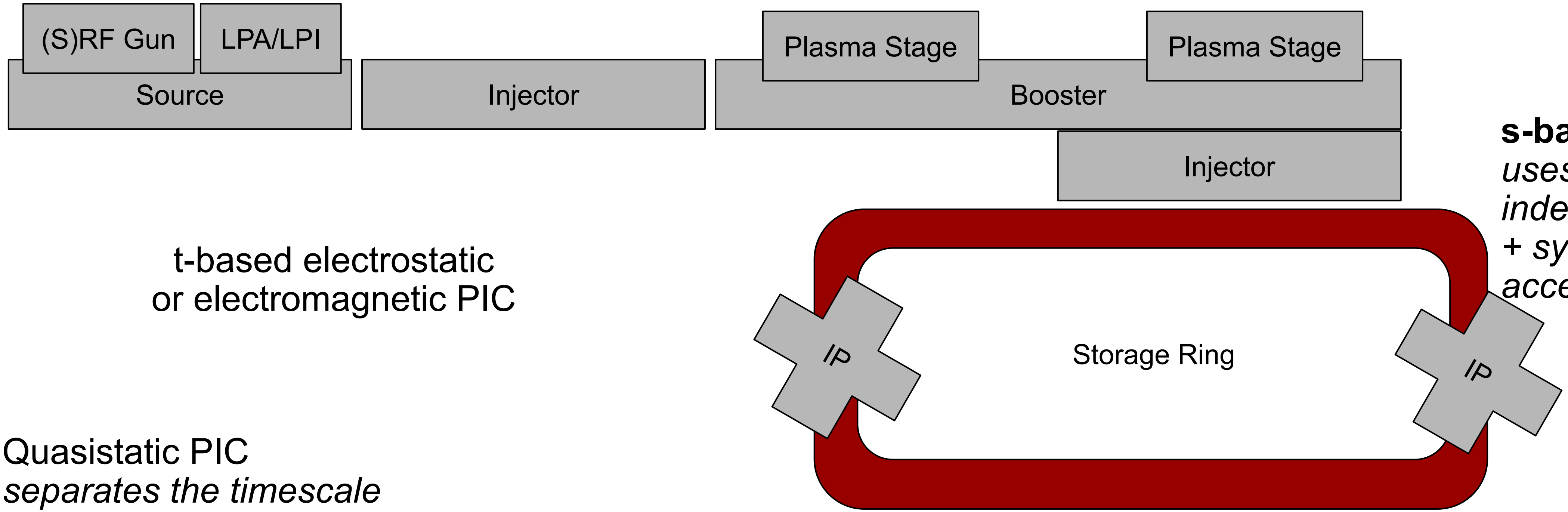

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or electromagnetic PIC

Quasistatic PIC
separates the timescale for plasma wakefield and beam evolution

buildup of electron clouds, secondary electron yield

Goal
Start-to-end modeling in an open software ecosystem.

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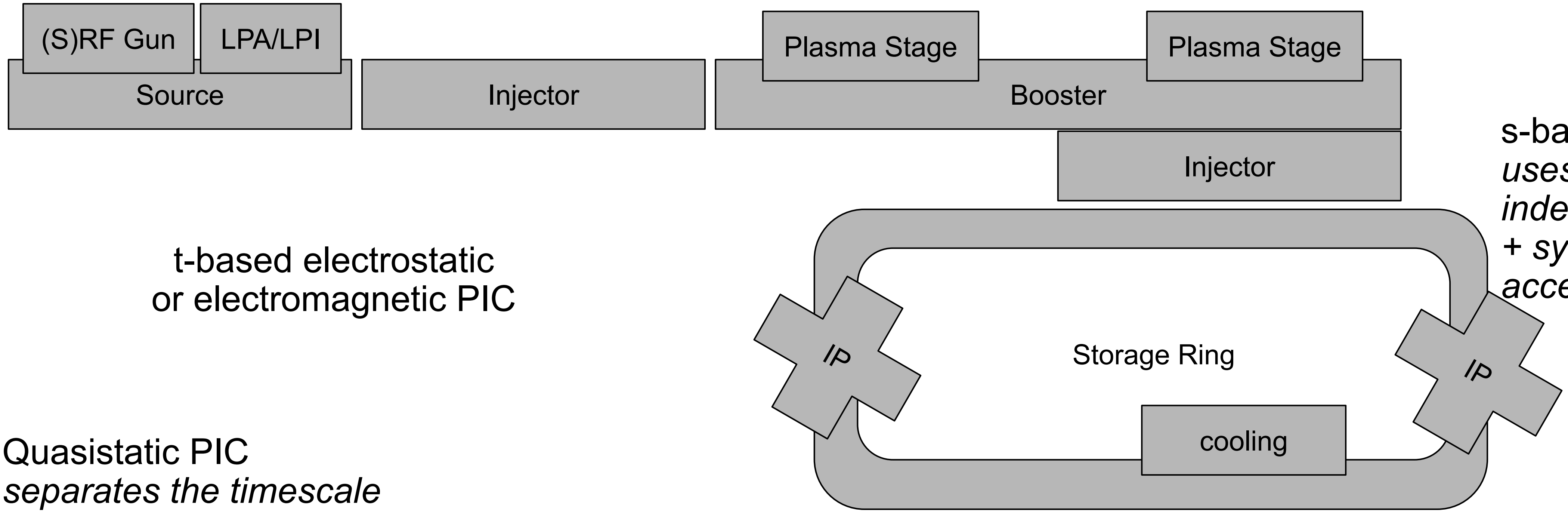

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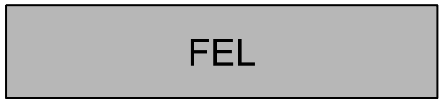
buildup of electron clouds, secondary electron yield

modeling of radiative & space-charge effects



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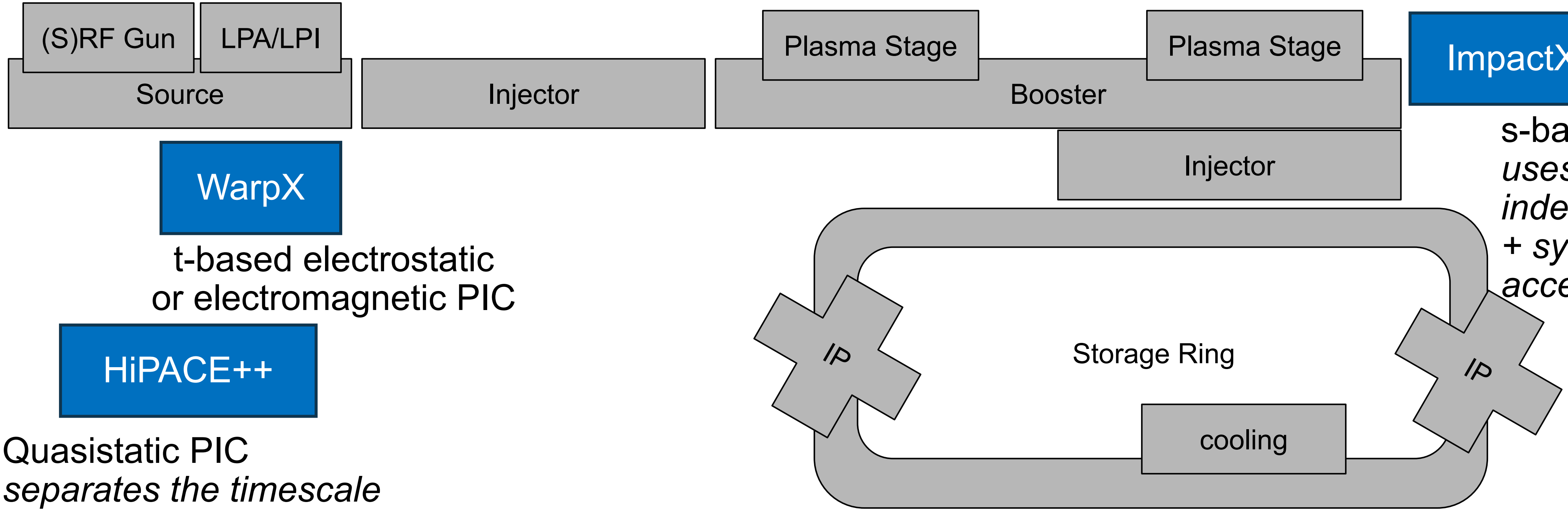

ImpactX

s-based PIC
uses s instead of t as independent variable + symplectic maps for accelerator elements

WarpX

t-based electrostatic or electromagnetic PIC

HiPACE++

Quasistatic PIC
separates the timescale for plasma wakefield and beam evolution

buildup of electron clouds, secondary electron yield

modeling of radiative & space-charge effects

FEL

Legend

BLAST: Exascale

Goal
Start-to-end modeling in an open software ecosystem.

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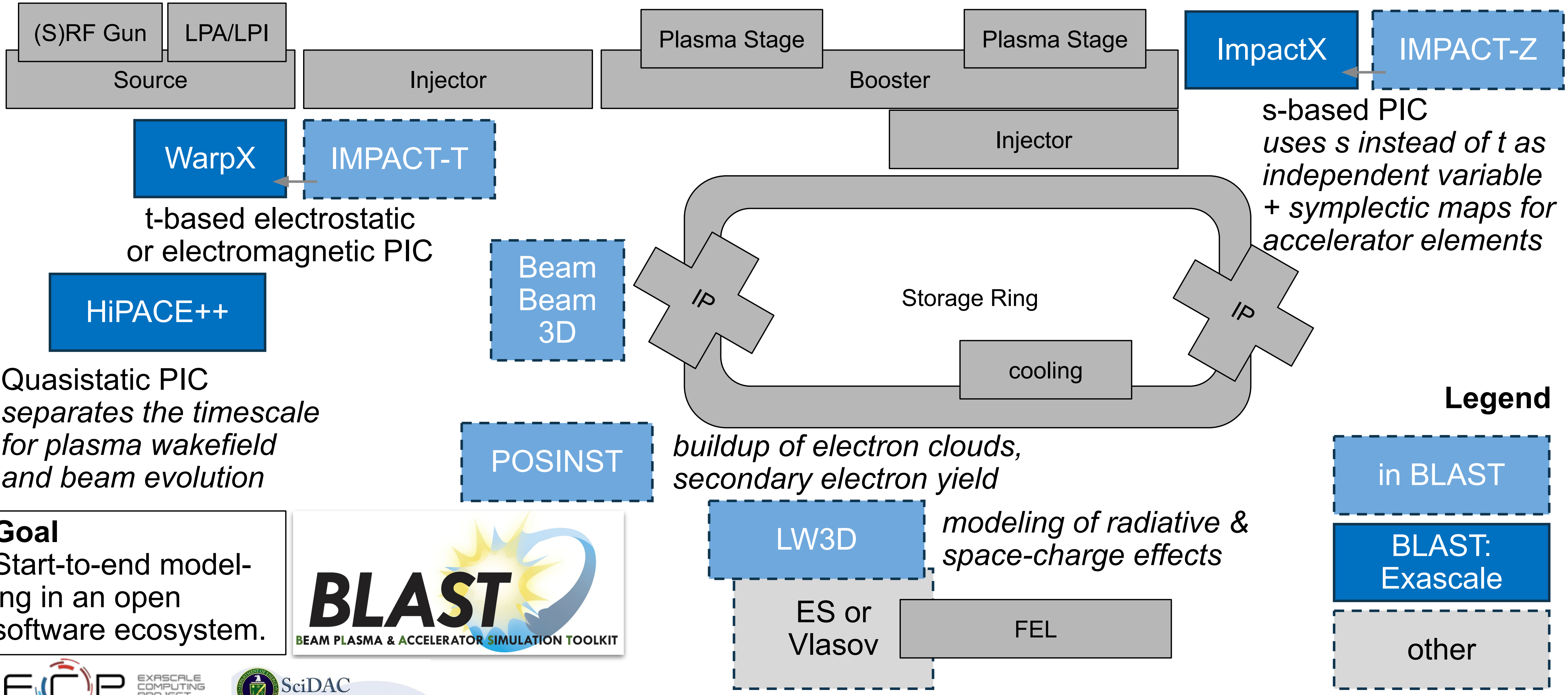

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Start-to-end modeling in an open software ecosystem.

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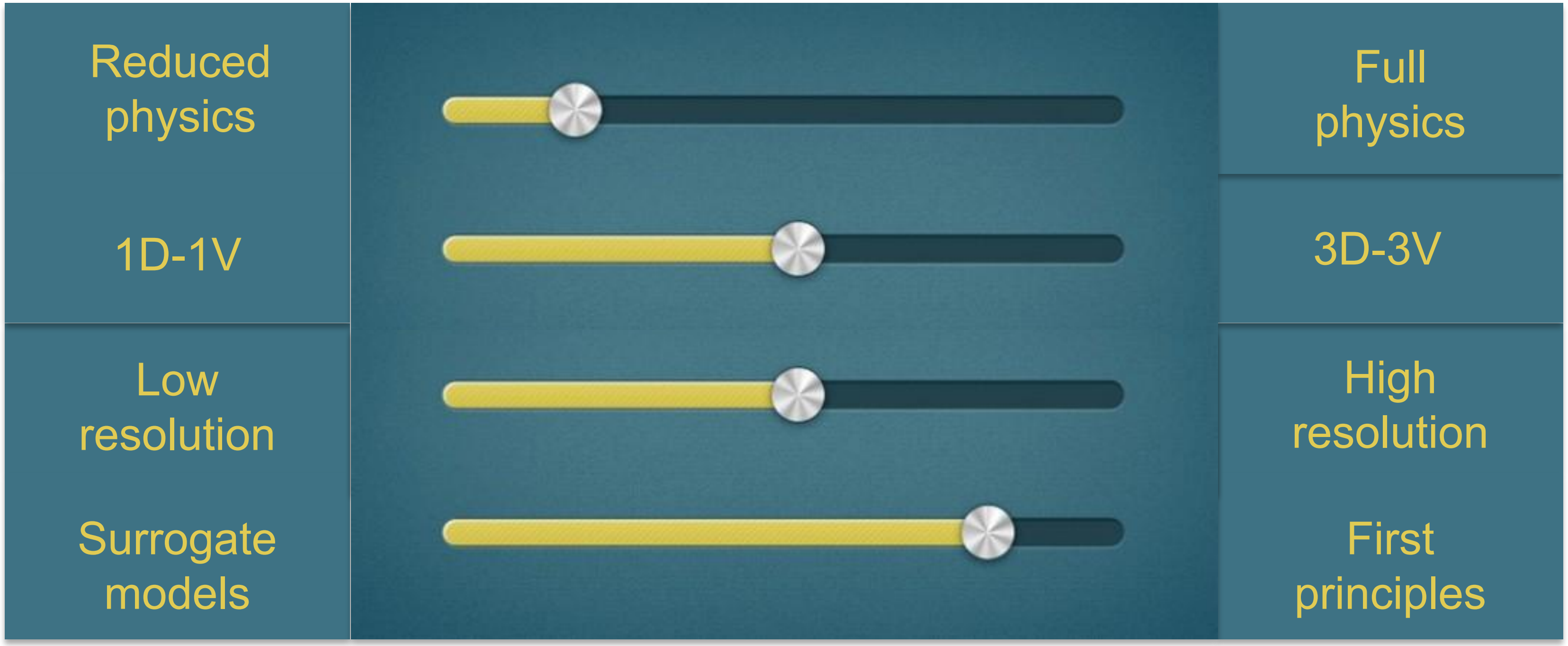
Ultimate goal: offer on-the-fly tunability of physics & numerics complexity to users

Great for ensemble runs for design studies



Great for detailed runs for physics studies

Goal
Start-to-end modeling in an open software ecosystem.

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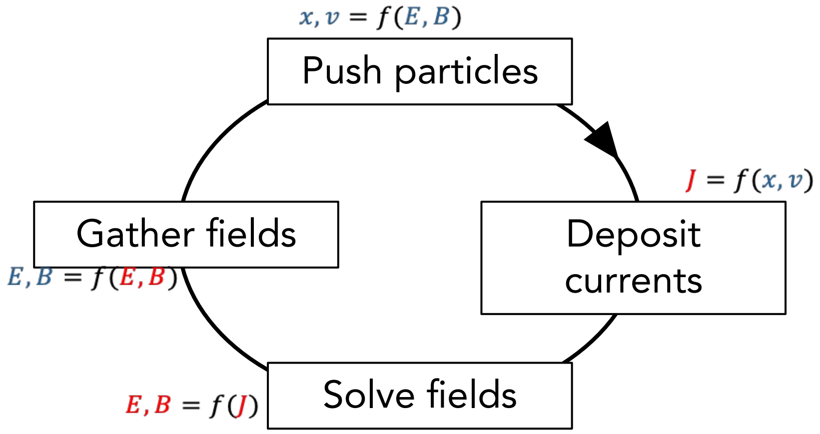
Start-to-End Modeling R&D

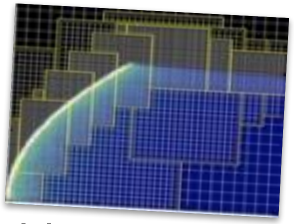
- advanced models: numerics, AI/ML surrogates
- speed & scalability: team science with computer sci.
- flexibility & reliability: modern software ecosystem

Overview of the Particle-In-Cell code WarpX

Available Particle-in-Cell Loops

- electrostatic & electromagnetic (fully kinetic)





Advanced algorithms

boosted frame, spectral solvers, Galilean frame, embedded boundaries + CAD, MR, ...

Multi-Physics Modules

field ionization of atomic levels, Coulomb collisions, QED processes (e.g. pair creation), macroscopic materials

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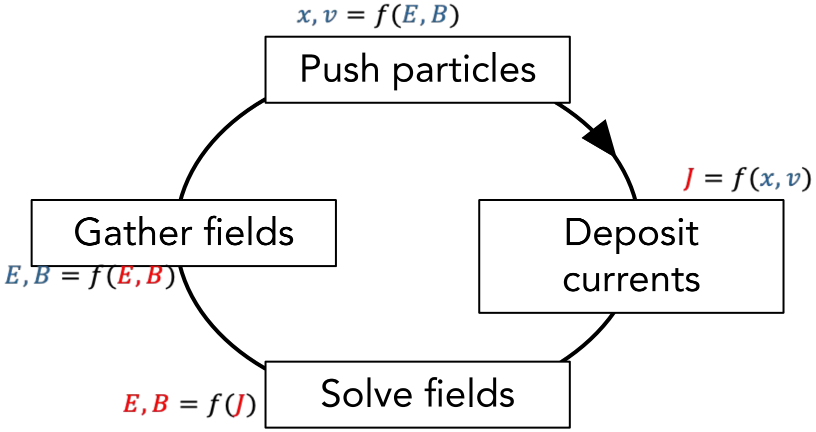

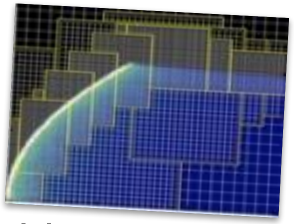

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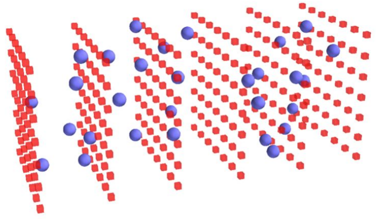
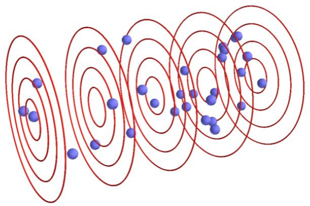
Geometries

- 1D3V, 2D3V, 3D3V and RZ (spectral cylindrical)



3D Cartesian grid



Cylindrical grid (schematic)

Multi-Node parallelization

- MPI: 3D domain decomposition
- dynamic load balancing

On-Node Parallelization

- GPU: CUDA, HIP and SYCL
- CPU: OpenMP

Scalable, Parallel I/O

- AMReX plotfile and openPMD (HDF5 or ADIOS)
- in situ diagnostics

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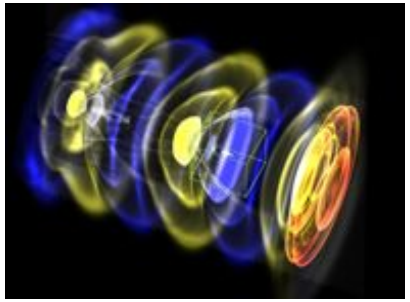
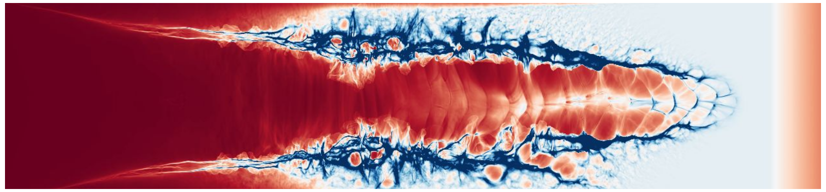
WarpX supports a growing number of applications

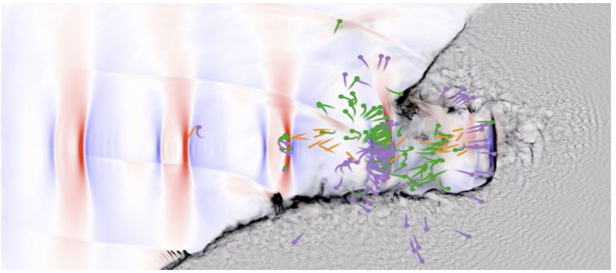


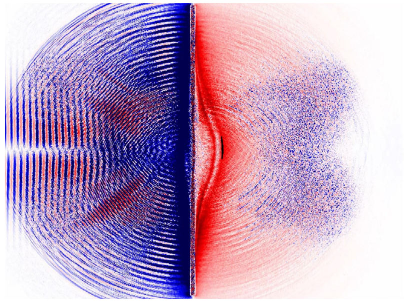
Plasma accelerators (LBNL, DESY, SLAC)

Laser-ion acceleration - advanced mechanisms (LBNL)



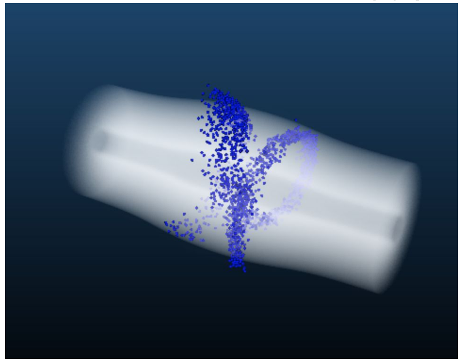
Plasma mirrors and high-field physics + QED (CEA Saclay/LBNL)



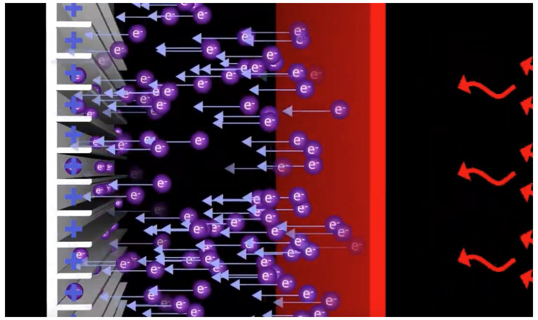


Laser-ion acceleration - laser pulse shaping (LLNL)

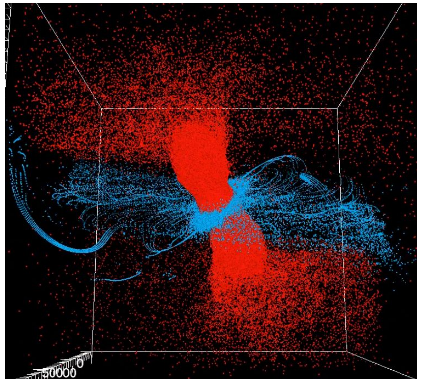
Plasma confinement, fusion devices (Zap Energy, Avalanche Energy)



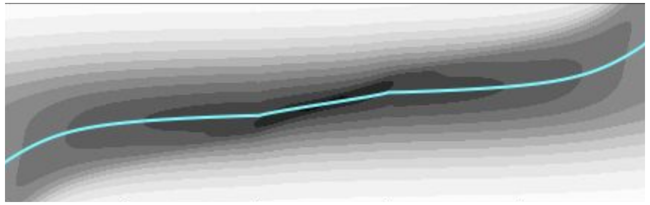
Thermionic converter (Modern Electron)



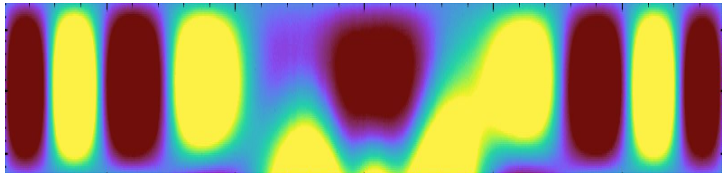
Pulsars, magnetic reconnection (LBNL)

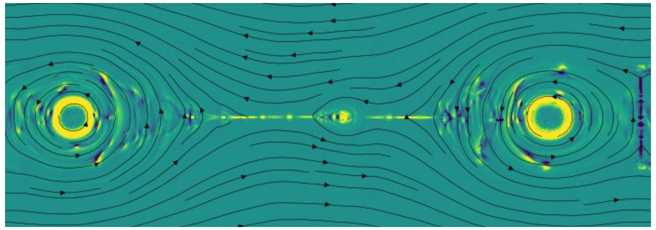


Magnetic fusion sheaths (LLNL)



Microelectronics (LBNL) - ARTEMIS





ImpactX: GPU-, AMR- & AI/ML-Accelerated Beam Dynamics

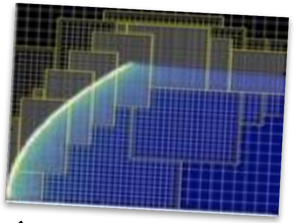
Last month, we open sourced ImpactX as an early developer preview.

Particle-in-Cell Loop

- electrostatic
  - with space-charge effects (in dev.)
- s-based
  - relative to a reference particle
  - elements: symplectic maps

Fireproof Numerics

based on IMPACT suite of codes, esp. IMPACT-Z and MaryLie



Triple Acceleration Approach

- GPU support
- Adaptive Mesh Refinement (in dev.)
- AI/ML & Data Driven Models (in dev.)

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github.com/ECP-WarpX/impactx

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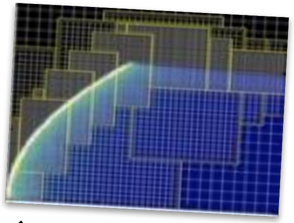

Triple Acceleration Approach

- GPU support
- Adaptive Mesh Refinement (in dev.)
- AI/ML & Data Driven Models (in dev.)

User-Friendly

- single-source C++, full Python control
- fully tested
- fully documented

Multi-Node parallelization

- MPI: 2D/3D domain decomposition
- dynamic load balancing (in dev.)

On-Node Parallelization

- GPU: CUDA, HIP and SYCL
- CPU: OpenMP

Scalable, Parallel I/O (in dev.)

- openPMD
- in situ analysis/visualization

github.com/ECP-WarpX/impactx

ImpactX: Physics Benchmark Examples

- FODO cell
- magnetic bunch compression chicane
- stationary beam in a const. focusing channel
- Kurth-distr. beam in periodic isotropic focusing channel
- stable FODO cell + short RF (buncher) cavities for longitudinal focusing
- chain of thin multipoles
- nonlin. focusing channel (IOTA nonlin. lens)
- Fermilab IOTA storage ring (linear optics)

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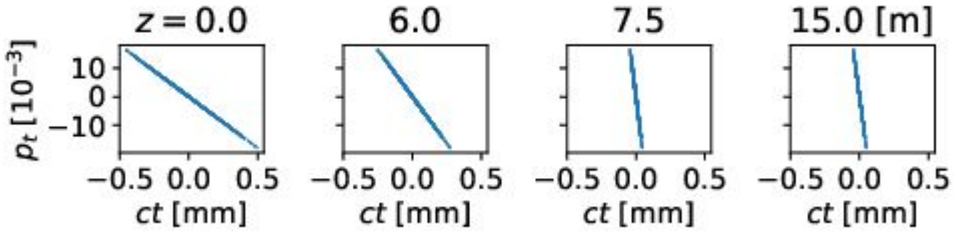
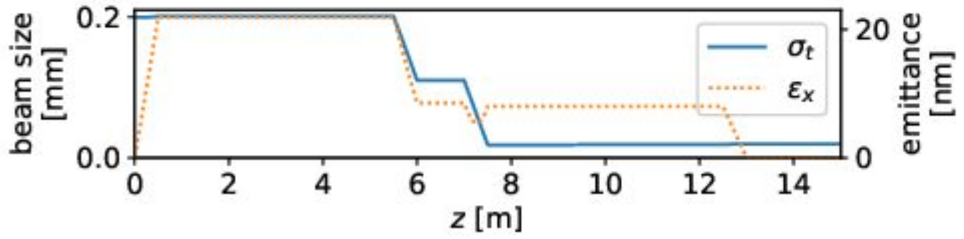
Berlin-Zeuthen Chicane

- rms-matched 5 GeV electron beam with initial normalized transverse rms emittance of 1 μm
- LCLS (@5GeV) & TESLA XFEL (@500MeV)-like



- longitudinal phase space: 10x compression
- emittance coupling: recovered at exit



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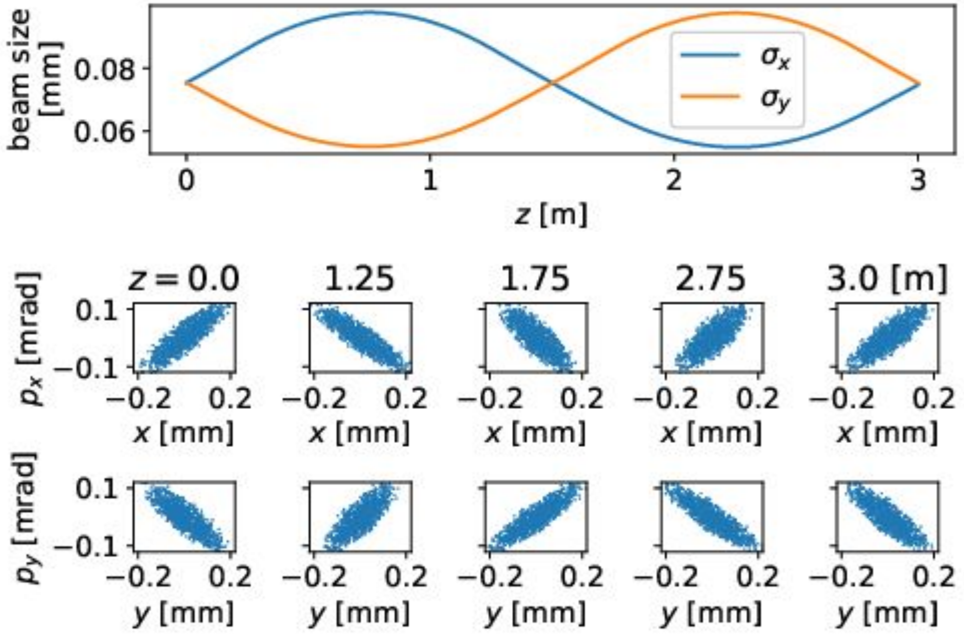
FODO Cell

- stable FODO lattice with a zero-current phase advance of 67.8 degrees per cell
- rms-matched 2 GeV electron beam with initial unnormalized rms emittance of 2 nm
  - test also checks if emittance stays flat



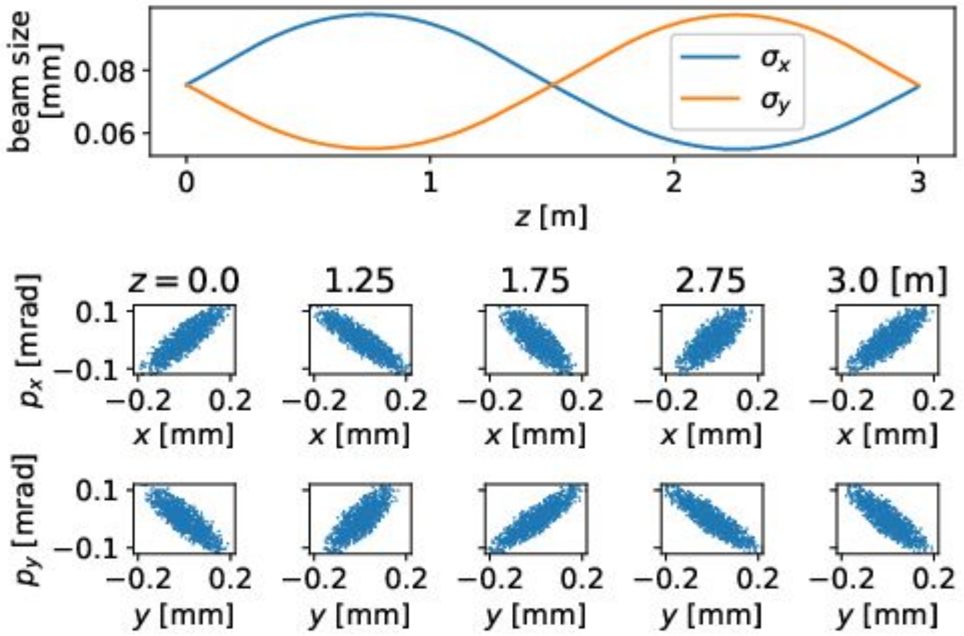
ImpactX: Physics Benchmark Examples

```python
from impactx import ImpactX, RefPart, \
                    distribution, elements

sim = ImpactX()  # simulation object

# set numerical parameters and IO control
sim.set_particle_shape(2)  # B-spline order
sim.set_slice_step_diagnostics(True)
sim.set_space_charge(False)

# domain decomposition & space charge mesh
sim.init_grids()

# load a 2 GeV electron beam with an initial
# unnormalized rms emittance of 2 nm
energy_MeV = 2.0e3  # reference energy
charge_C = 1.0e-9  # used with space charge
mass_MeV = 0.510998950  # mass
qm_qeeV = -1.0e-6/mass_MeV  # charge/mass
npart = 10000  # number of macro particles
distr = distribution.Waterbag(
    sigmaX = 3.9984884770e-5,
    sigmaY = 3.9984884770e-5,
    sigmaT = 1.0e-3,
    sigmaPx = 2.6623538760e-5,
    sigmaPy = 2.6623538760e-5,
    sigmaPt = 2.0e-3,
    muxpx = -0.846574929020762,
    muypy = 0.846574929020762,
    mutpt = 0.0)
sim.add_particles(
    qm_qeeV, charge_C, distr, npart)

# set the energy in the reference particle
sim.particle_container().ref_particle() \
    .set_energy_MeV(energy_MeV, mass_MeV)

# design the accelerator lattice
ns = 25  # steps slicing through ds
fodo = [
    elements.Drift(ds=0.25, nslice=ns),
    elements.Quad(ds=1.0, k=1.0, nslice=ns),
    elements.Drift(ds=0.5, nslice=ns),
    elements.Quad(ds=1.0, k=-1.0, nslice=ns),
    elements.Drift(ds=0.25, nslice=ns)
]
# assign a fodo segment
sim.lattice.extend(fodo)

# run simulation
sim.evolve()
```

💡 **Same Script**
CPU/GPU & MPI

FODO Cell

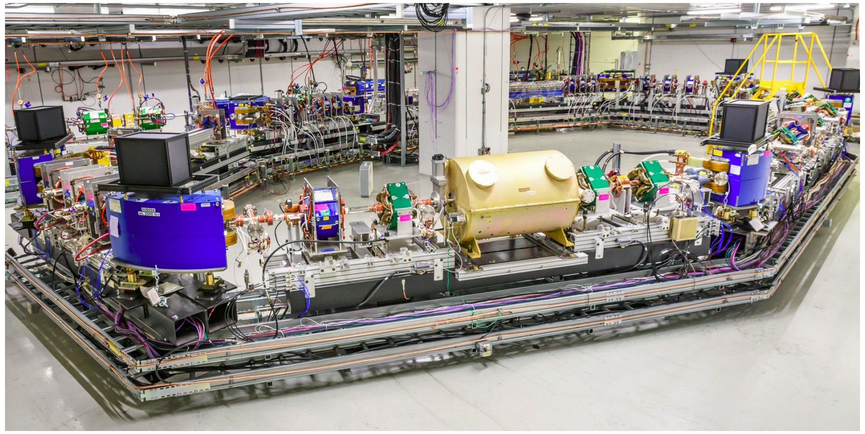
- stable FODO lattice with a zero-current phase advance of 67.8 degrees per cell
- rms-matched 2 GeV electron beam with initial unnormalized rms emittance of 2 nm
  - test also checks if emittance stays flat



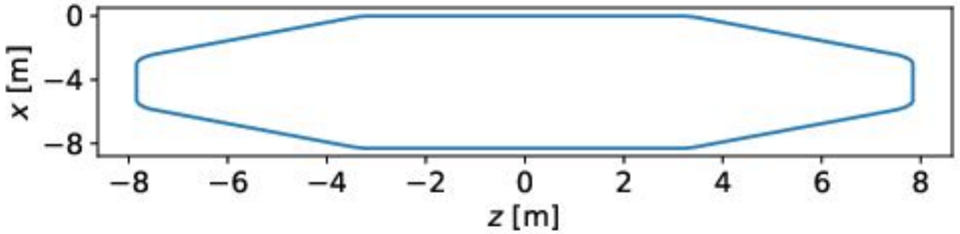
EXASCALE COMPUTING PROJECT
BERKELEY LAB
LDRD

ImpactX: IOTA (v8.4) Lattice Benchmark @2.5 MeV protons

bare (linear) lattice of the Fermilab IOTA storage ring; an rms-matched proton beam with an un-normalized emittance of 4.5 µm propagates over a single turn



Reference Orbit



EXASCALE COMPUTING PROJECT

BERKELEY LAB

LDRD

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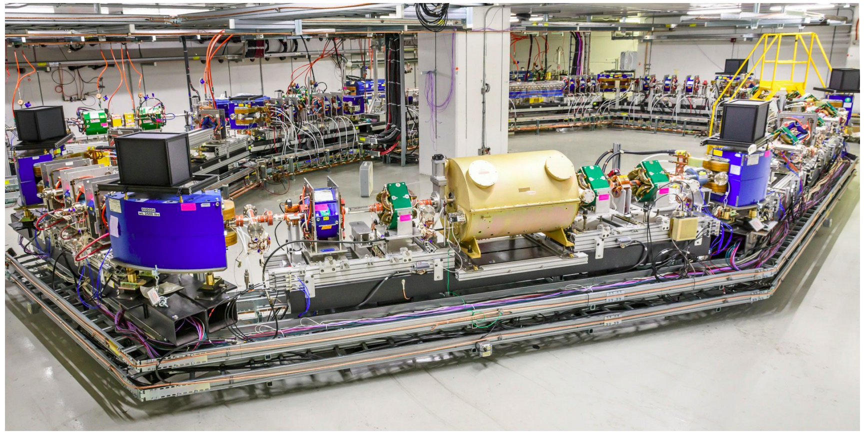

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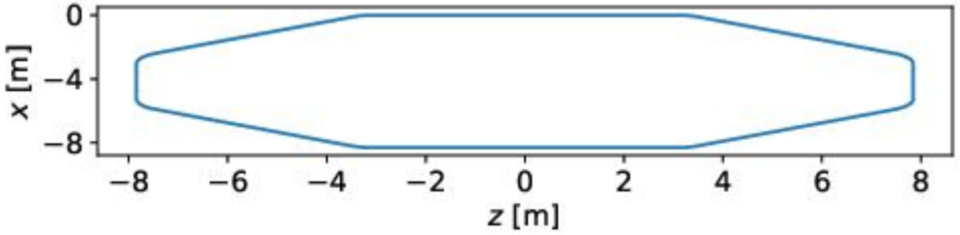
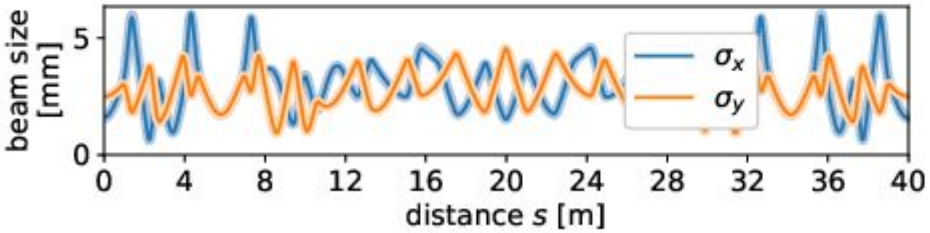


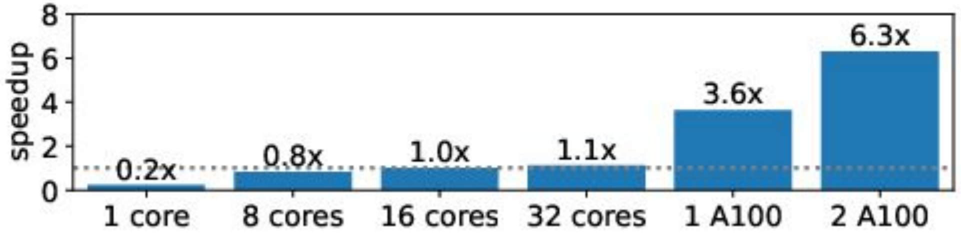
Preservation of Second Moments

- nnl. element: conserve invariants of motion
- check emittance preservation
- rms beam size evolution:
  IMPACT-Z vs ImpactX



Preliminary Performance

- on Perlmutter (NERSC) CPU / GPU
- order-of-magnitude perf.↗ w/o dyn. LB (yet)



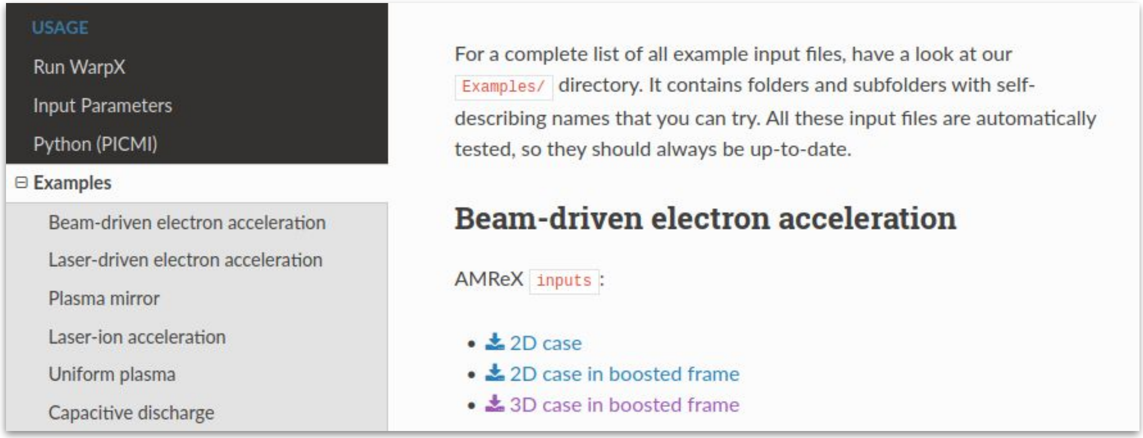
EXASCALE COMPUTING PROJECT

BERKELEY LAB

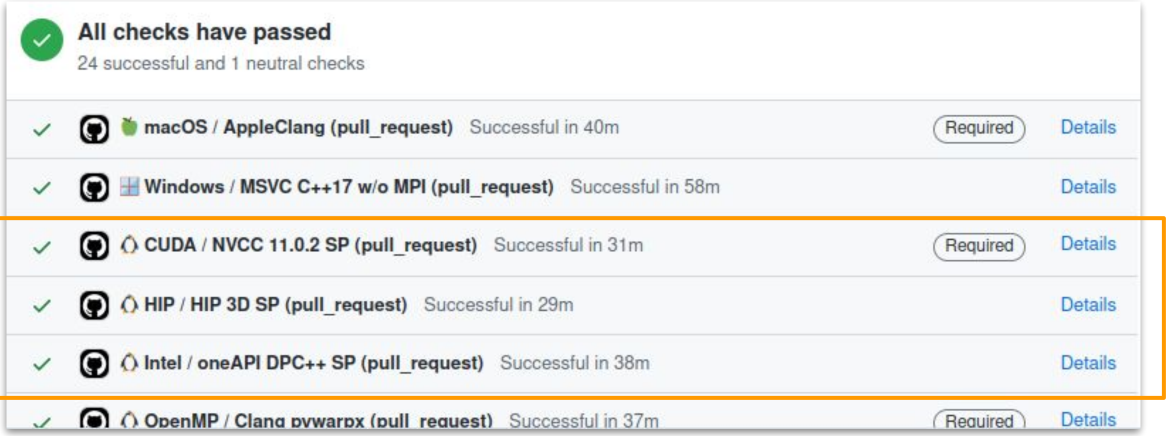
LDRD

An open interface with the community

Online Documentation:
warpx|hipace|impactx.readthedocs.io



Open-Source Development & Benchmarks:
github.com/ECP-WarpX



188 physics benchmarks *run on every code change* of WarpX
8 physics benchmarks + 32 tests *for* ImpactX

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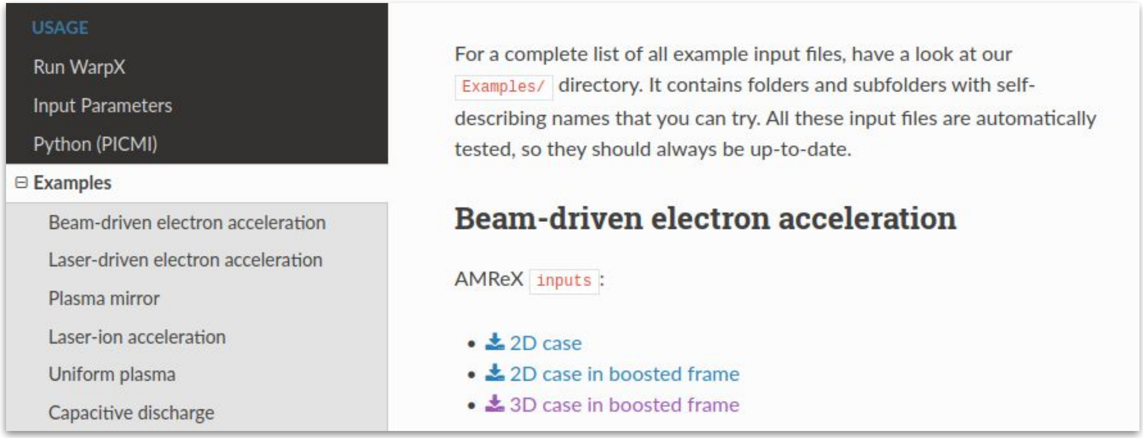

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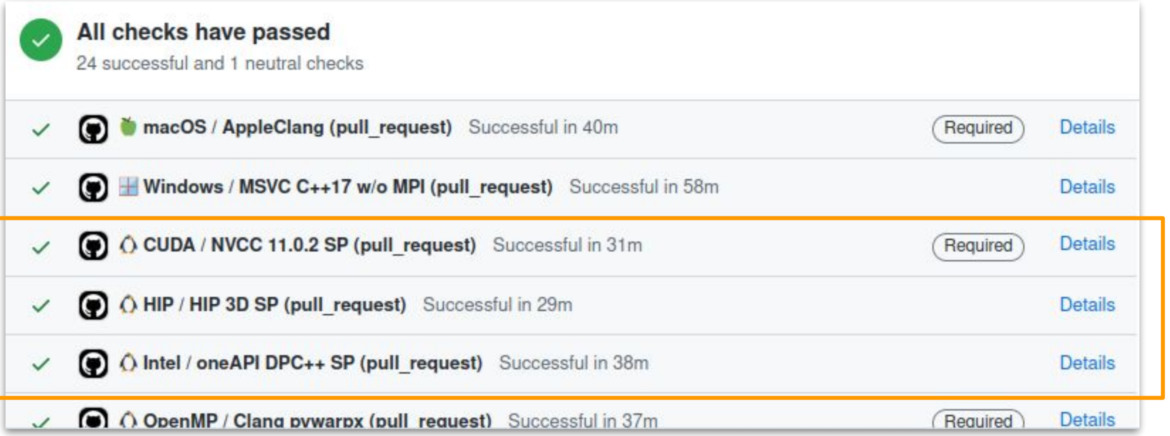


188 physics benchmarks *run on every code change* of WarpX
8 physics benchmarks + 32 tests *for* ImpactX

Rapid and easy installation on any platform:

python3 -m pip install .

brew tap ecp-warpx/warpx
brew install warpx

cmake -S . -B build
cmake --build build --target install

conda install
-c conda-forge warpx

spack install warpx
spack install py-warpx

module load warpx
module load py-warpx

EXASCALE COMPUTING PROJECT

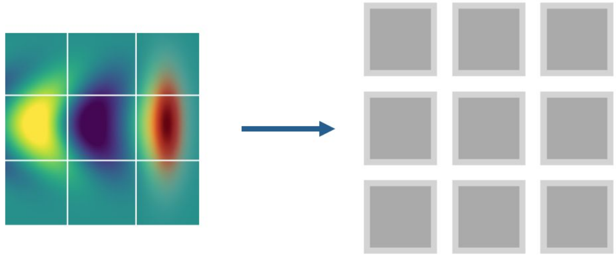
BERKELEY LAB LDRD

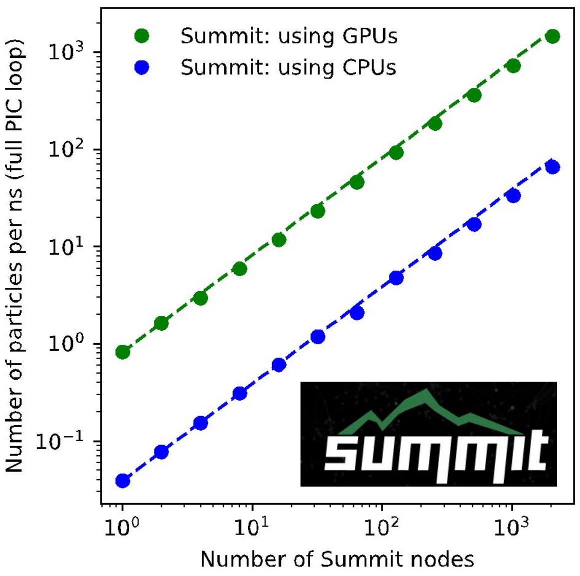
Portable Performance through Exascale Programming Model

AMReX library

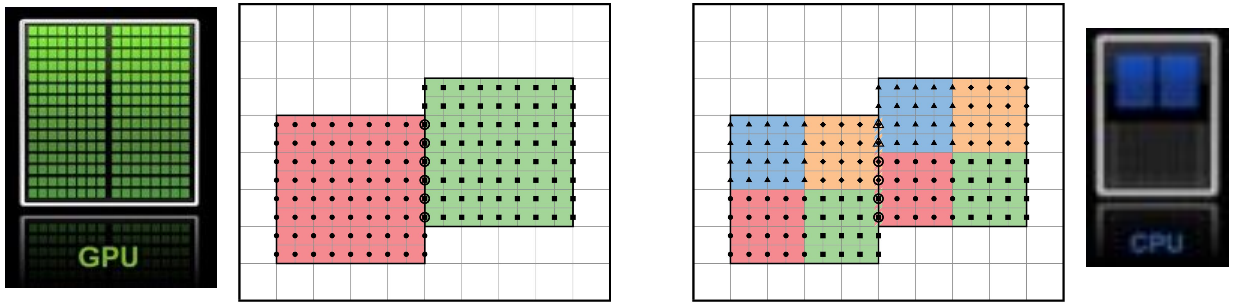
EXASCALE COMPUTING PROJECT

- Domain decomposition & MPI **communications:** MR & load balance





- **Performance-Portability Layer:** GPU/CPU/KNL



without tiling

with tiling

Data Structures

A. Myers et al., “Porting WarpX to GPU-accelerated platforms,” Parallel Computing 108, 102833 (2021)

Portable Performance through Exascale Programming Model

AMReX library

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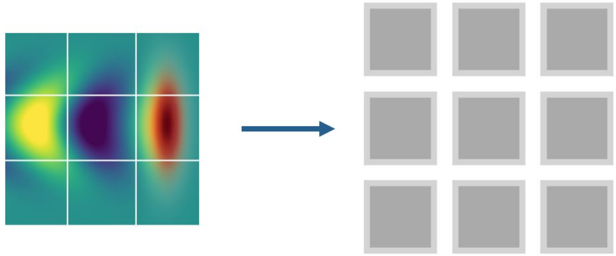

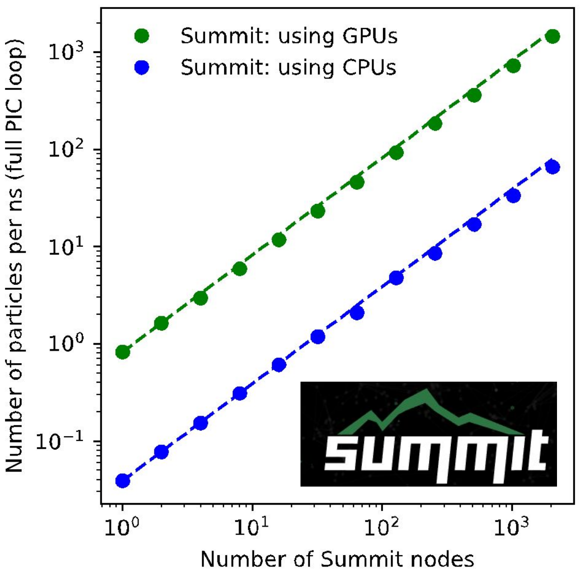

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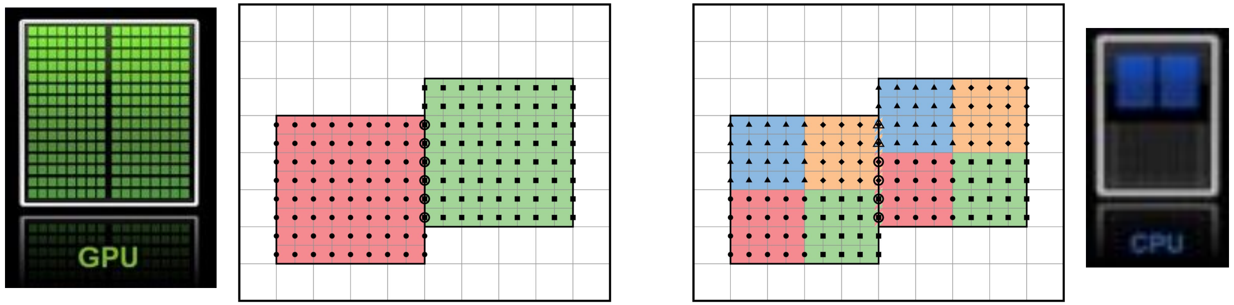


without tiling

with tiling

Data Structures

- **Write the code once**, specialize at ***compile-time***

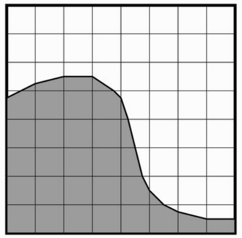
`ParallelFor(/Scan/Reduce)`

```
amrex::ParallelFor( n_particles,
    [=] AMREX_GPU_DEVICE (long i) {

        UpdatePosition( x[i], y[i], z[i],
                        ux[i], uy[i], uz[i], dt );

    });
```

- **Parallel linear solvers** (e.g. multi-grid Poisson solvers)
- **Embedded boundaries**



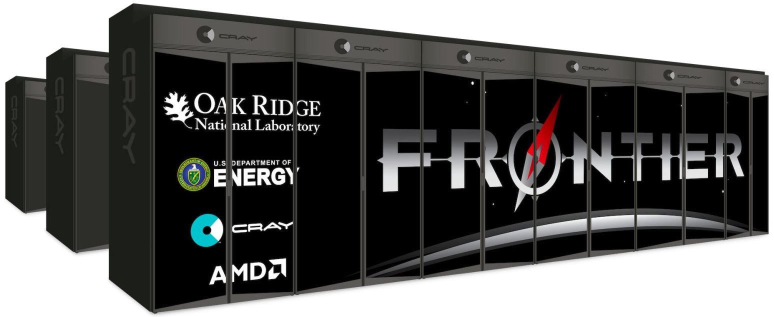
- Runtime parser for user-provided math expressions (incl. GPU)

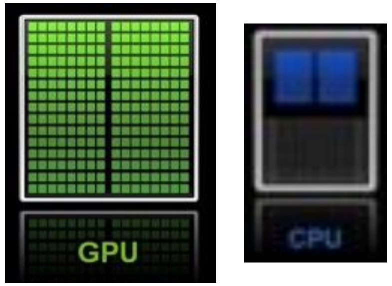
A. Myers et al., "Porting WarpX to GPU-accelerated platforms," Parallel Computing 108, 102833 (2021)

Transitioning to an Integrated Ecosystem

BLAST
BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

Desktop
to
HPC

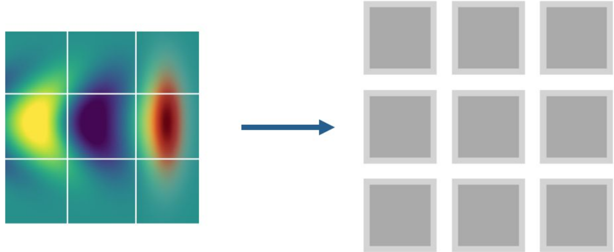




MPI	CUDA, OpenMP, SYCL, HIP

Transitioning to an Integrated Ecosystem

BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT



Desktop
to
HPC

AMReX

Containers, Communication, Portability, Utilities

FFT

on- or multi-device

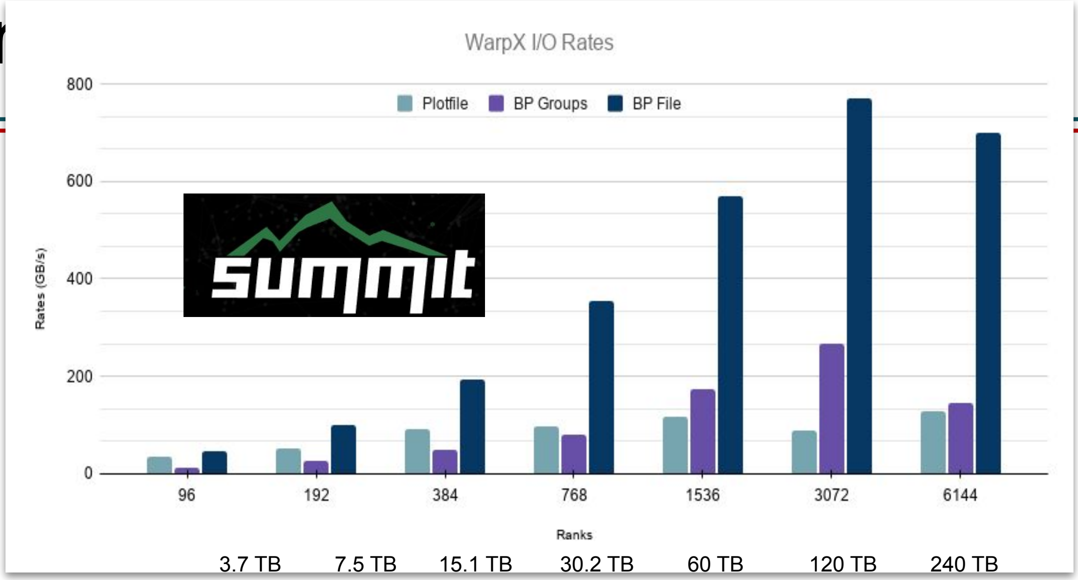
Lin. Alg.

BLAS++
LAPACK++

MPI

CUDA, OpenMP, SYCL, HIP

Transitioning to an I



BLAST
BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

- PByte-scale
- TByte/s Bandwidth

Desktop to HPC

AMReX

Containers, Communication, Portability, Utilities

Diagnostics

I/O

code coupling

openPMD

ADIOS2

HDF5

ZFP

...

Ascent

VTK-m

FFT

on- or multi-device

Lin. Alg.

BLAS++

LAPACK++

MPI

CUDA, OpenMP, SYCL, HIP

Transitioning to an Integrated Ecosystem

BLAST
BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

QED events

PICSAR
QED Modules

ABLASTR library: common PIC physics

AMReX

Containers, Communication, Portability, Utilities

Diagnostics
I/O
code coupling

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BLAS++
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MPI

CUDA, OpenMP, SYCL, HIP

mac OS

Desktop to HPC

ECP

Transitioning to an Integrated Ecosystem

BLAST
BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

WarpX
full PIC, LPA/LPI

HiPACE++
quasi-static, PWFA

ARTEMIS
microelectronics

ImpactX
accelerator lattice design

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Containers, Communication, Portability, Utilities

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. . .

Ascent

VTK-m

FFT
on- or multi-device

Lin. Alg.
BLAS++
LAPACK++

MPI

CUDA, OpenMP, SYCL, HIP

mac OS

Desktop to HPC

ECP PROJECT

Transitioning to an Integrated Ecosystem

BLAST
BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

Python: Modules, PICMI interface, Workflows

WarpX
full PIC, LPA/LPI

HiPACE++
quasi-static, PWFA

ARTEMIS
microelectronics

ImpactX
accelerator lattice design

Object-Level Python Bindings
extensible, AI/ML

pyAMReX

PICSAR
QED Modules

ABLASTR library: common PIC physics

AMReX
Containers, Communication, Portability, Utilities

Diagnostics
I/O
code coupling

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...

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mac OS

Desktop to HPC

ECP

- BLAST: Beam pLasma Accelerator Simulation Toolkit
- IO, Standardization & Open Development
- HPC: The Exascale Computing Project and Beyond

We Standardize & Develop Scalable Data Methods

Start-to-end accelerator modeling requires data compatibility and control usability

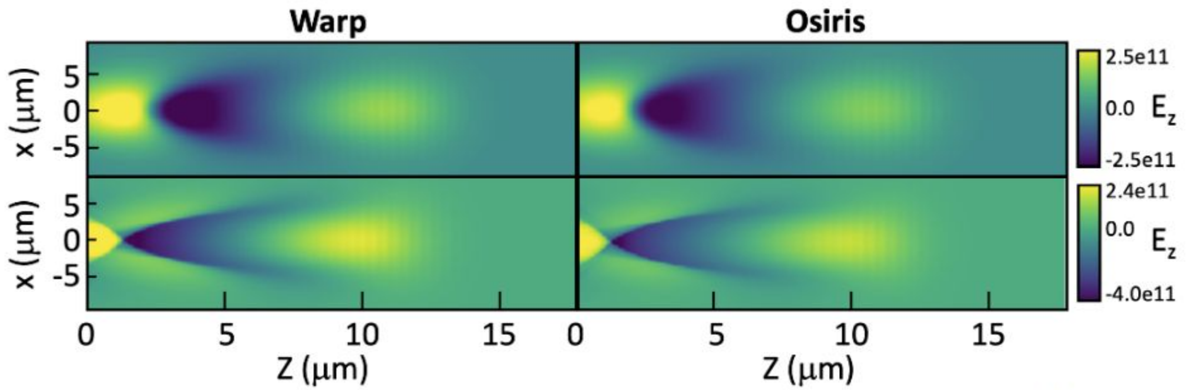

Figure 8: Longitudinal electric field (in V/m) in a laser-driven plasma acceleration stage at two times (top: $t \approx 300$fs, bottom: $t \approx 600$fs) along the laser propagation from 2-D PIC simulations with (left) Warp; (right) Osiris. Plots are based on rendering from the openPMD-viewer.

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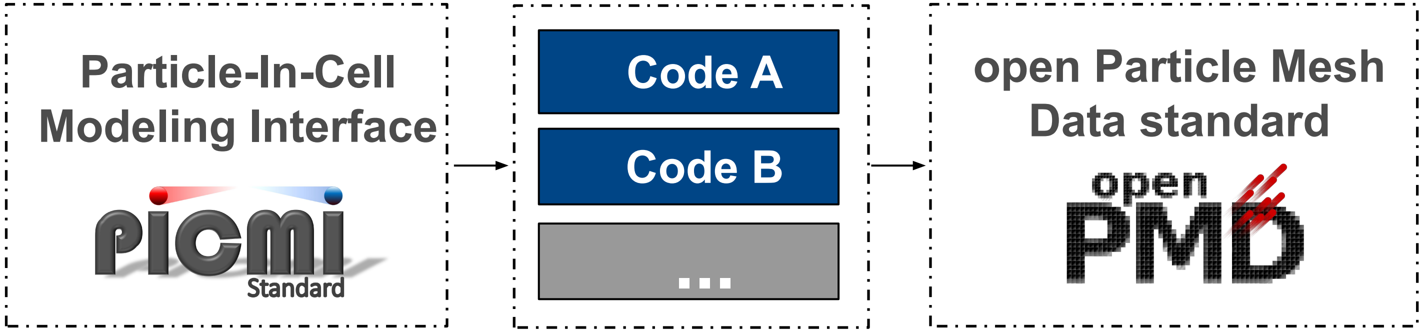

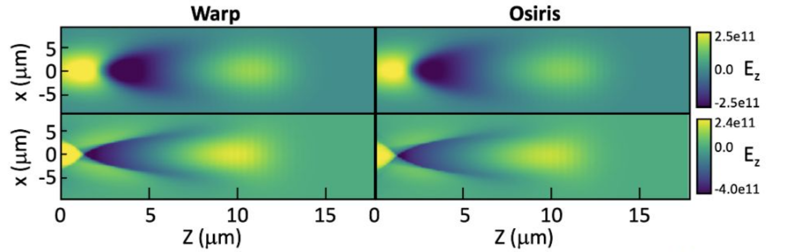

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Start-to-end accelerator modeling requires data compatibility and control usability

Particle-In-Cell Modeling Interface

PICMI Standard

→

Code A

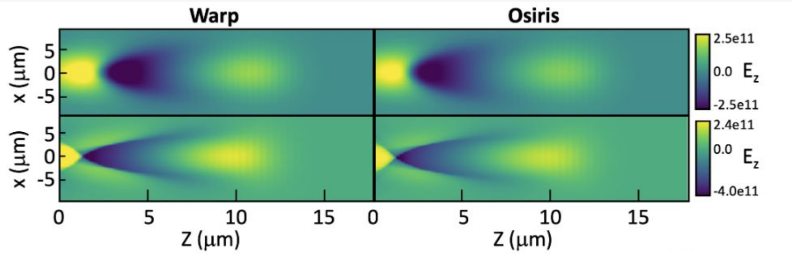
Code B

...

→

open Particle Mesh Data standard

openPMD



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Communities

Consortium for Advanced Modeling of Particle Accelerators CAMPA

Berkeley Lab, SLAC, Fermilab, UCLA

DOE HEP GARD - now DOE SciDAC-5

Lawrence Livermore National Laboratory, radiasoft, Tech-X

HZDR Helmholtz Zentrum Dresden Rossendorf, Berkeley Lab, CASUS Center for Advanced Systems Understanding, Oak Ridge National Laboratory, Technische Universität Dresden, European XFEL, Perimeter Institute, IOQ Jena Friedrich-Schiller-Universität, Lawrence Livermore National Laboratory, Fermilab, SLAC National Accelerator Laboratory, Maison de la Simulation, DESY, UHH, CBG Max Planck Institute of Molecular Cell Biology and Genetics, Cornell University, UCLA, NVIDIA, EUCALL, panosc photon and neutron open science cloud, plasmapy

SciDAC Scientific Discovery through Advanced Computing

openPMD: Open Standard for Particle-Mesh Data

- **markup** / schema for arbitrary hierarchical data formats
- truly, scientifically **self-describing**
- basis for **open data workflows**

openPMD standard (1.0.0, 1.0.1, 1.1.0)
the underlying file markup and definition
A Huebl et al., DOI:10.5281/zenodo.33624

EXASCALE COMPUTING PROJECT

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general description	domain specific

wavefronts, particle species, particle beams,weighted particles, PIC, MD, mesh-refinement, CCD images, ...

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wavefronts, particle species, particle beams,weighted particles, PIC, MD, mesh-refinement, CCD images, ...

ADIOS HDF {JSON}

openPMD-viewer
quick visualization
explore, e.g., in Jupyter

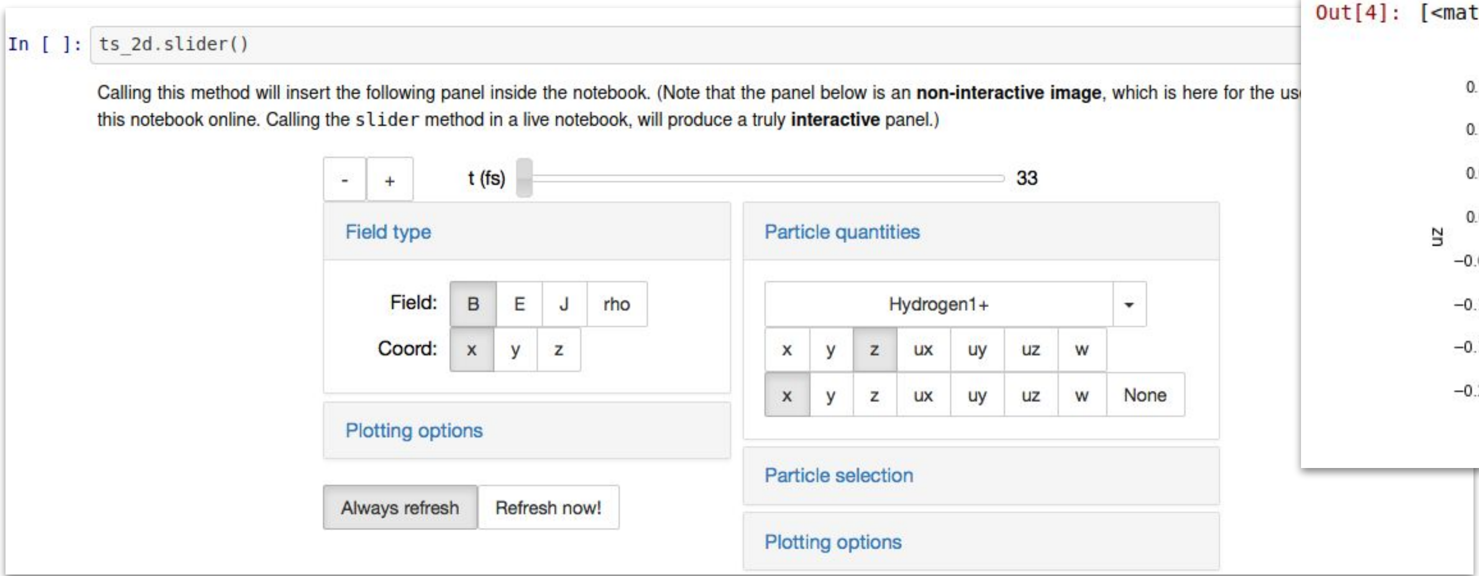
openPMD-api
reference library
file-format agnostics API

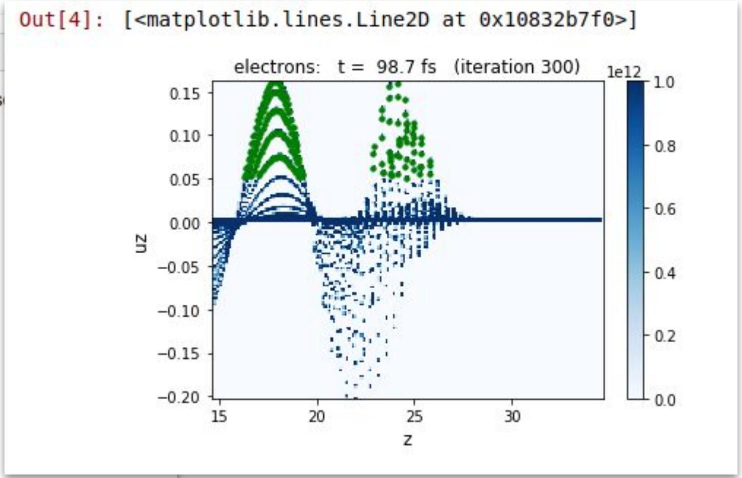
openPMD-updater
auto-update to new standard, verify
openPMD-validator

We Standardize & Develop Scalable Data Methods

… and integrate them for scientific productivity

including data analytics frameworks & graphical user interfaces





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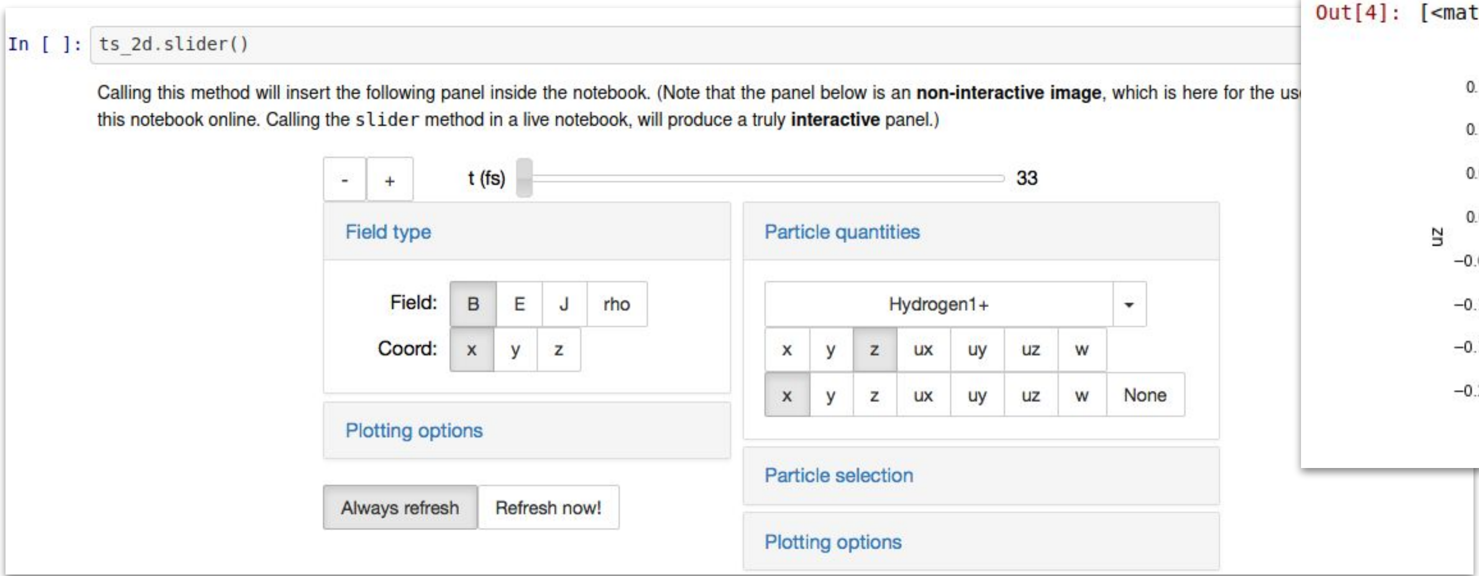

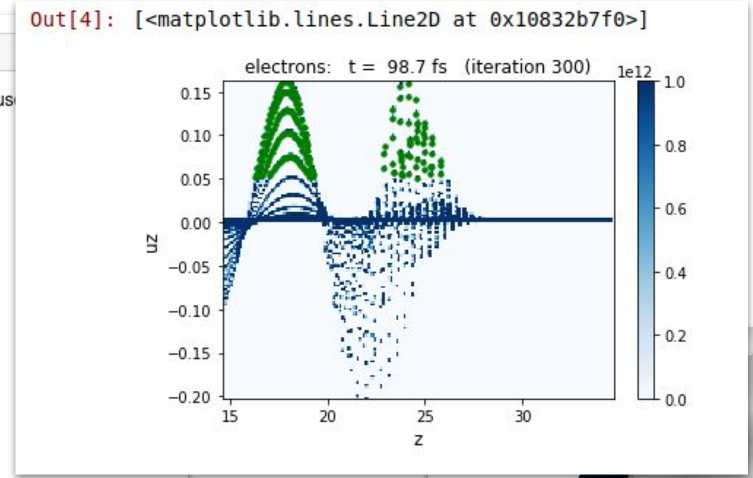

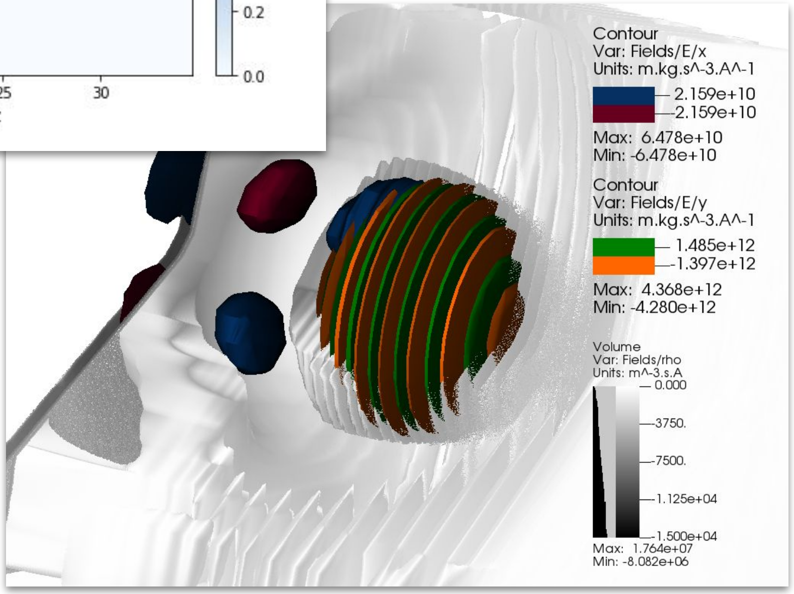

openPMD DASK ParaView yt VisIt

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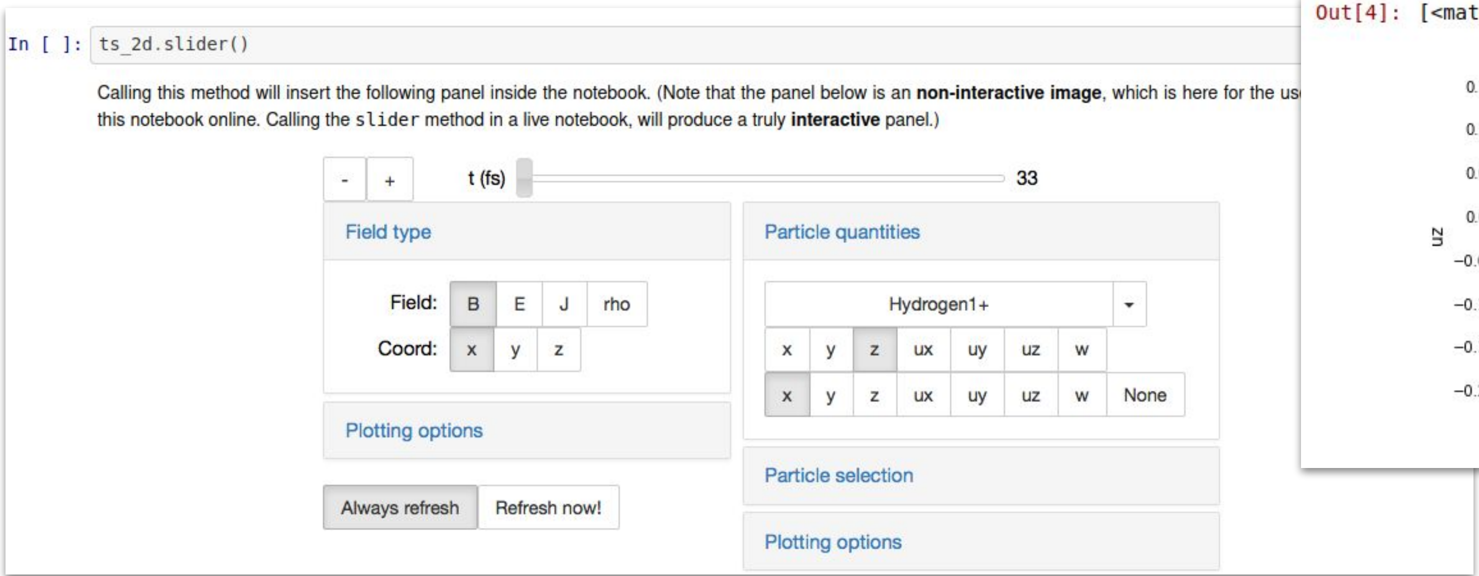

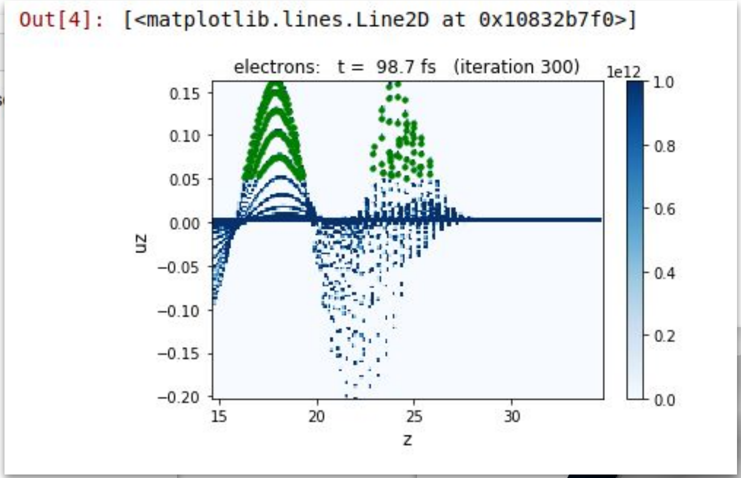

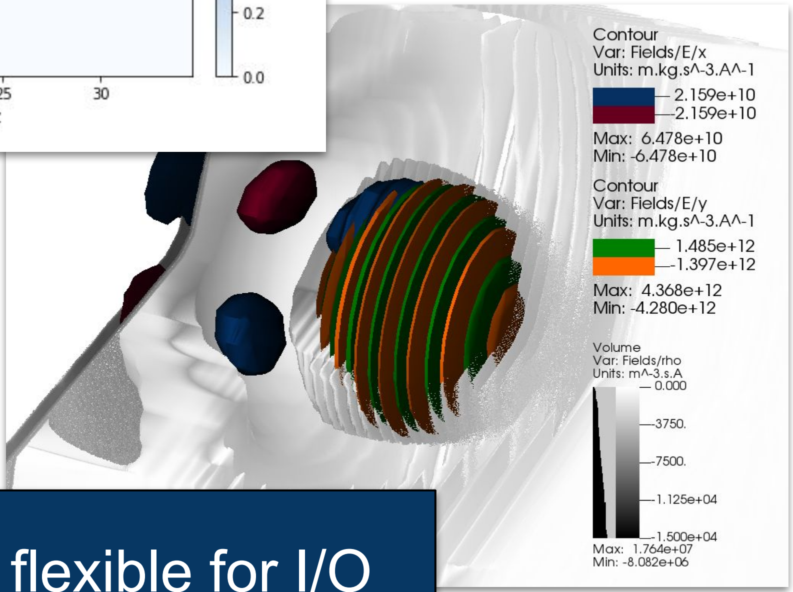

Open standardization, i.e. openPMD, makes us flexible for I/O libraries, tooling & domain-science needs.

EXASCALE COMPUTING PROJECT

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WarpX: Runs Efficiently on the *First Exascale Supercomputer*

April-July 2022: ran on **world's largest HPCs**
L. Fedeli, A. Huebl et al., *accepted* in SC'22, 2022

Note: Perlmutter & Frontier are pre-acceptance!

Demonstrated scaling **4-5 orders** of magnitude

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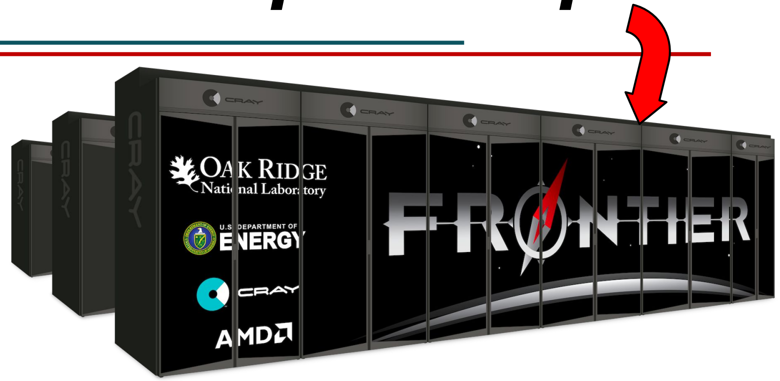

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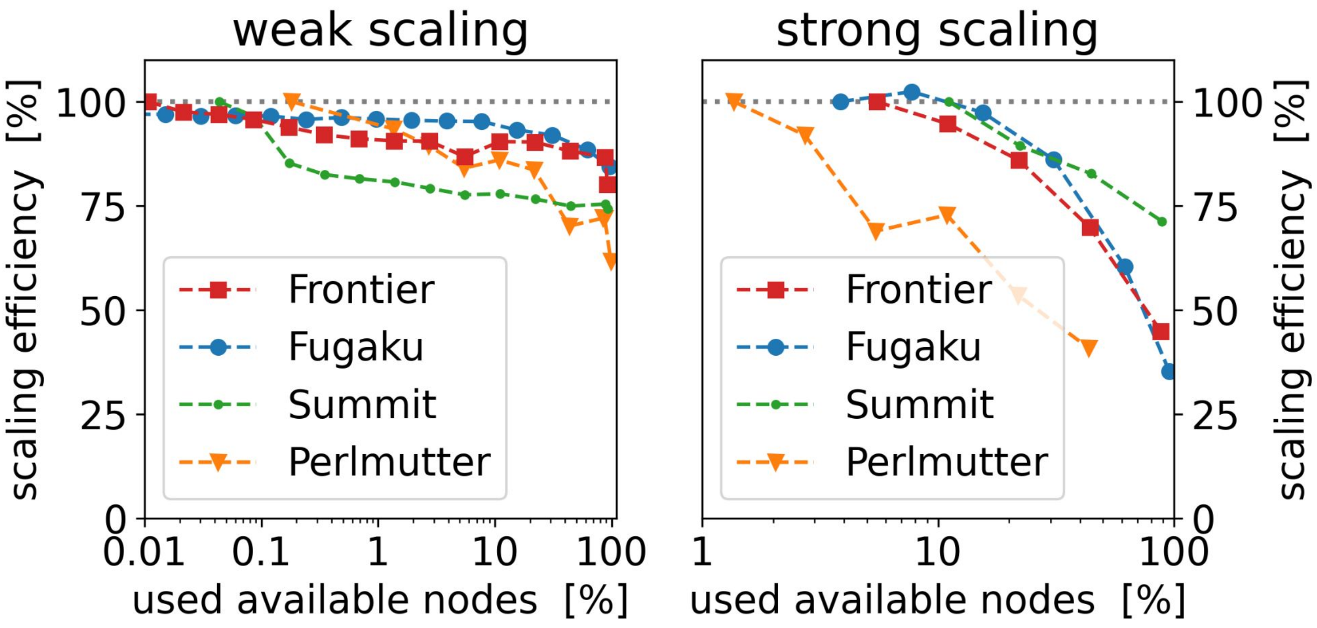

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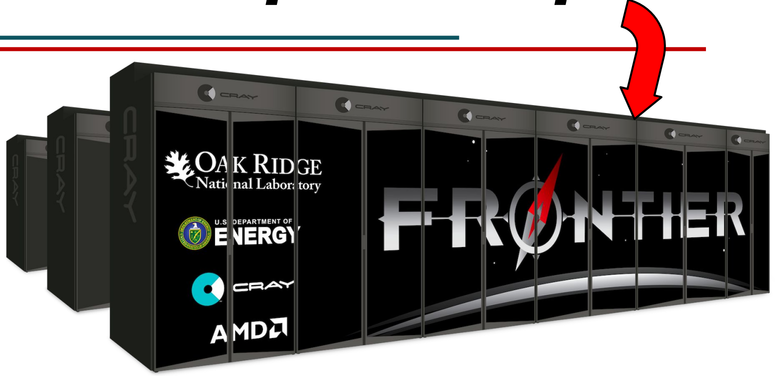
L. Fedeli, A. Huebl et al., *accepted* in SC'22, 2022

Note: Perlmutter & Frontier are pre-acceptance!



Demonstrated scaling **4-5 orders** of magnitude

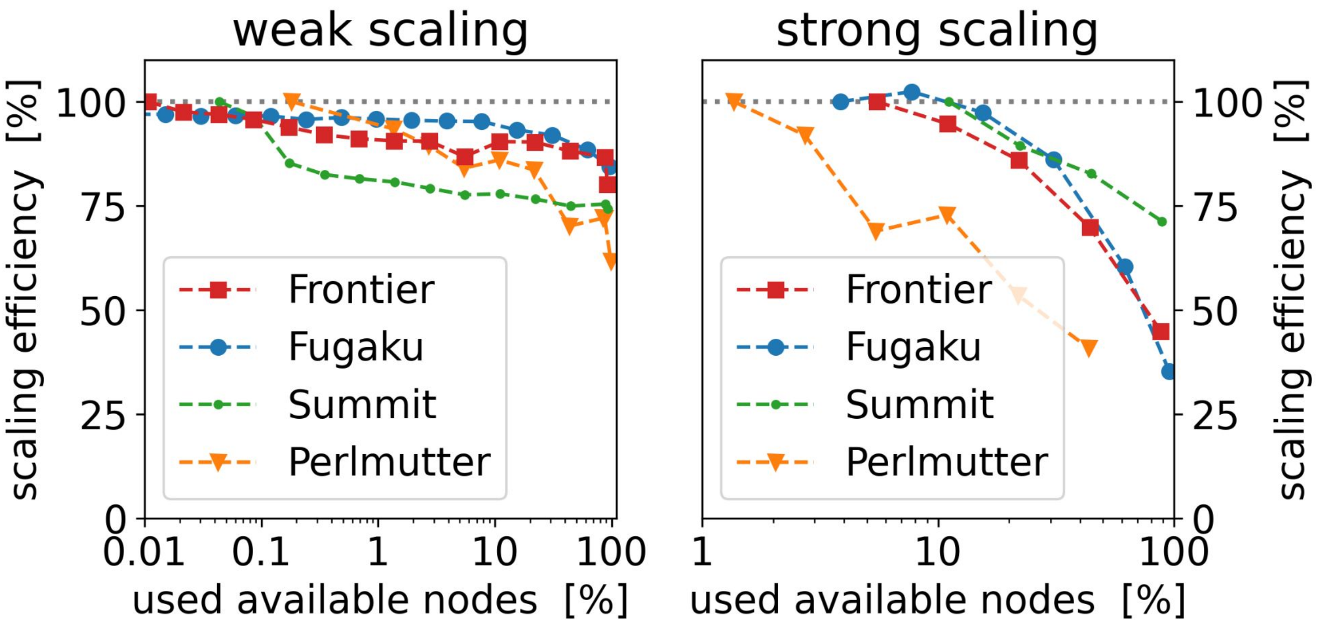


Figure-of-Merit over time

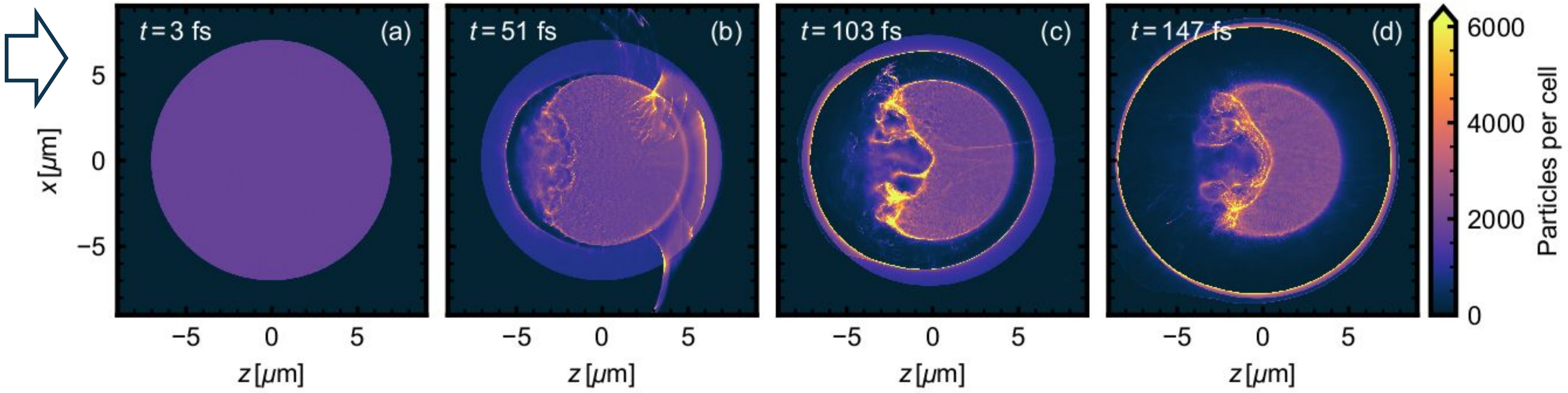
Date	Machine	N_C/Node	Nodes	FOM
3/19	Cori	0.4e7	6 625	1.0e11
6/19	Summit	2.8e7	1 000	7.8e11
9/19	Summit	2.3e7	2 560	6.8e11
1/20	Summit	2.3e7	2 560	1.0e12
2/20	Summit	2.5e7	4 263	1.2e12
6/20	Summit	2.0e7	4 263	1.4e12
7/20	Summit	2.0e8	4 263	2.5e12
3/21	Summit	2.0e8	4 263	2.9e12
6/21	Summit	2.0e8	4 263	2.7e12
7/21	Perlmutter	2.7e8	960	1.1e12
12/21	Summit	2.0e8	4 263	3.3e12
4/22	Perlmutter	4.0e8	928	1.0e12
4/22	Perlmutter†	4.0e8	928	1.4e12
4/22	Summit	2.0e8	4 263	3.4e12
4/22	Fugaku†	3.1e6	98 304	8.1e12
6/22	Perlmutter	4.4e8	1 088	1.0e12
7/22	Fugaku	3.1e6	98 304	2.2e12
7/22	Fugaku†	3.1e6	152 064	9.3e12
7/22	Frontier	8.1e8	8 576	1.1e13

110x

GPU Computing at Scale Requires Advanced Load Balancing

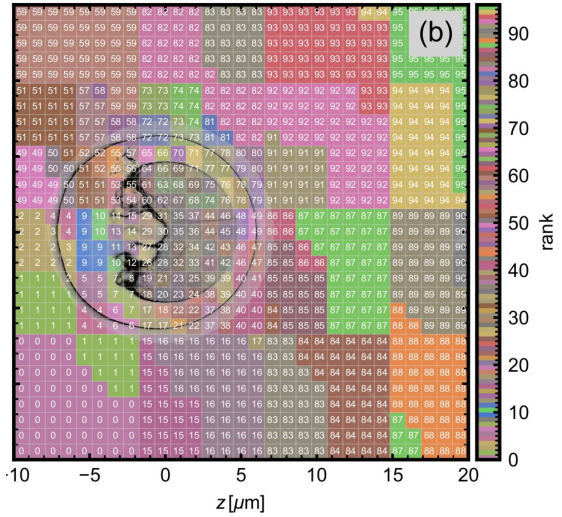
Application Challenges

- Plasma Mirrors & Laser-Ion Acceleration: moving front
- Laser Wakefield Accelerator: Injected Beam Particles



domain decomposition example:

Z-order space filling curve



M. Rowan, A. Huebl, K. Gott, R. Lehe, M. Thévenet, J. Deslippe, J.-L. Vay, "In-Situ Assessment of Device-Side Compute Work for Dynamic Load Balancing in a GPU-Accelerated PIC Code," PASC21, DOI:10.1145/3468267.3470614 (2021)

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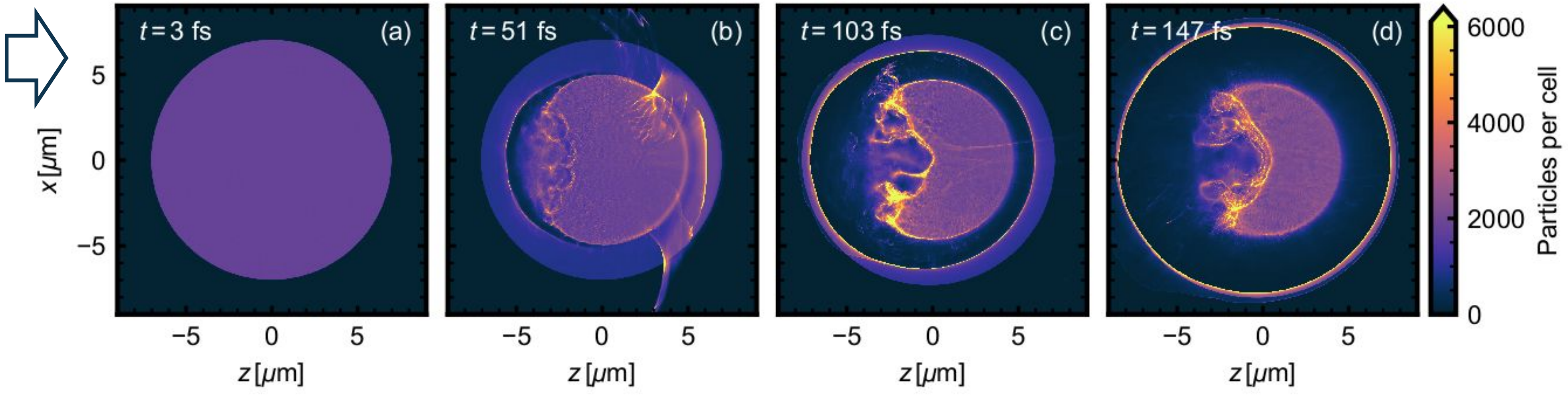

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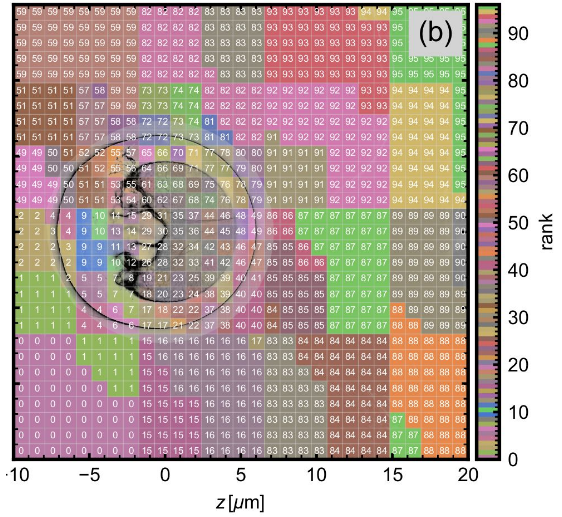
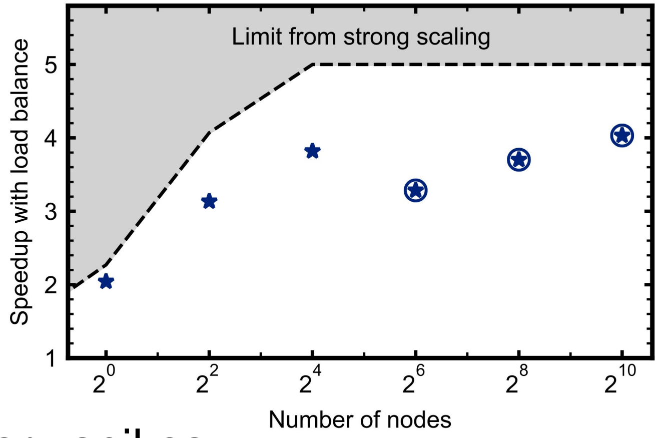


In Situ Cost Analysis

- basis for distribution functions
- realistic cost: kernel timing

Result: 3.8x speedup!

- production-quality, easy-to-use
- larger simulation: mitigate local memory spikes



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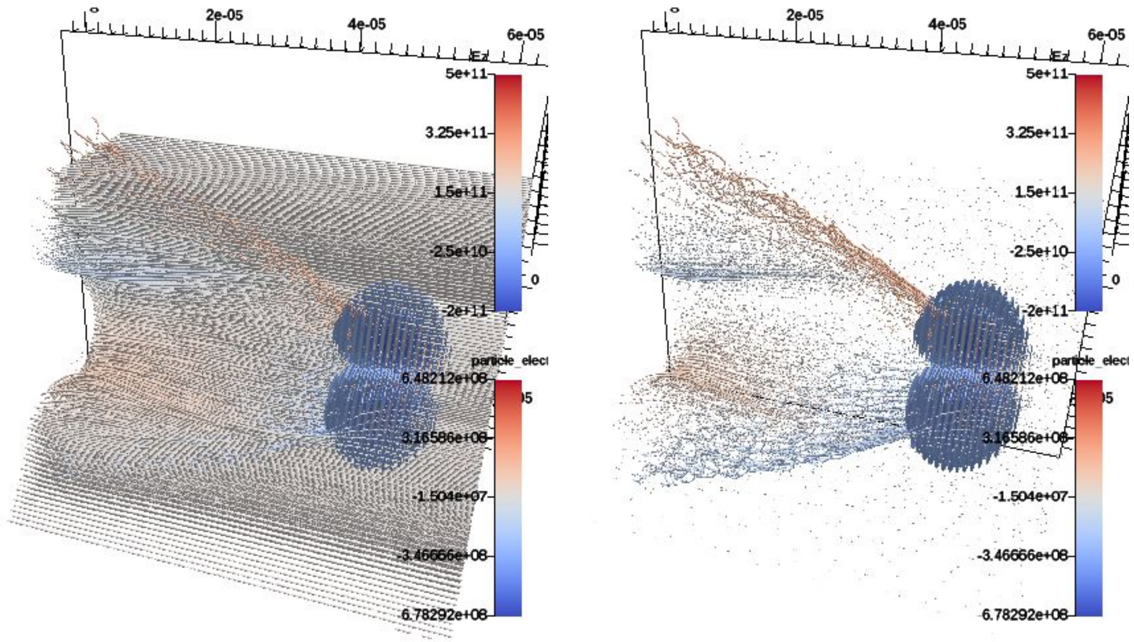
Novel Visualization Techniques

Particle *Adaptive Sampling*

- **emphasis** on “uncommon” properties
- inverse sampling to incidence of a property



A. Biswas et al., “In Situ Data-Driven Adaptive Sampling for Large-scale Simulation Data Summarization,” ISAV18 @SC18 (2018)

ALPINE: Ascent Biswas, Larsen, Lo

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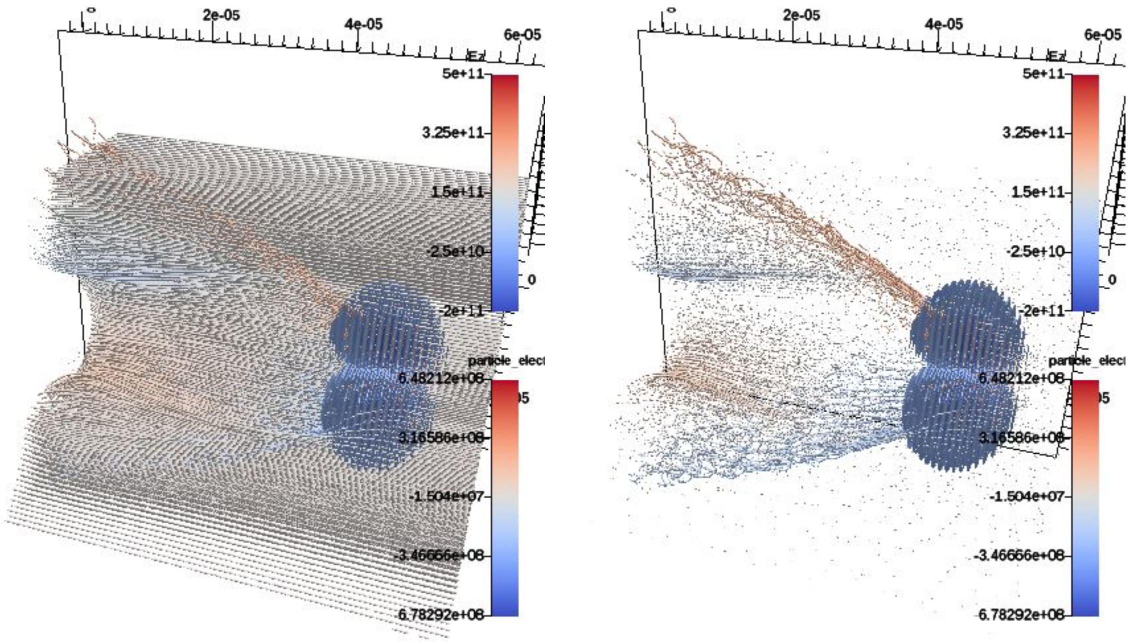

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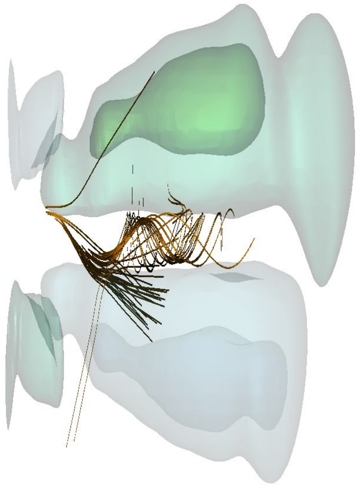
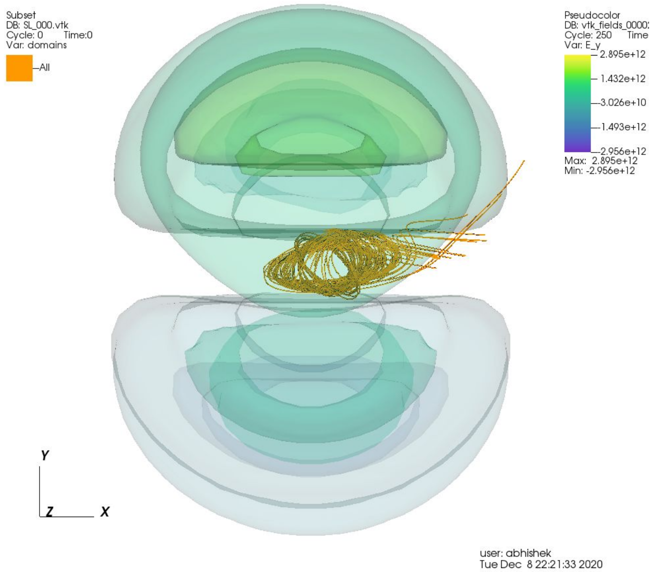
Physics-Informed Flow Tracelines

- traditional flow vis. depends only on *local field values*
- plasma particles:
    - **inert**: track *relativistic momentum* on a traceline
    - **Lorentz-Force**: 6 fields (electromag.), leap-frog
- chance to **significantly reduce particle I/O** in real-life workflows through savings on **temporal fidelity**





ALPINE: Ascent Biswas, Larsen, Lo

VTK-m Yenpure, Childs, Pugmire

Postdocs Welcome - Come work with us!

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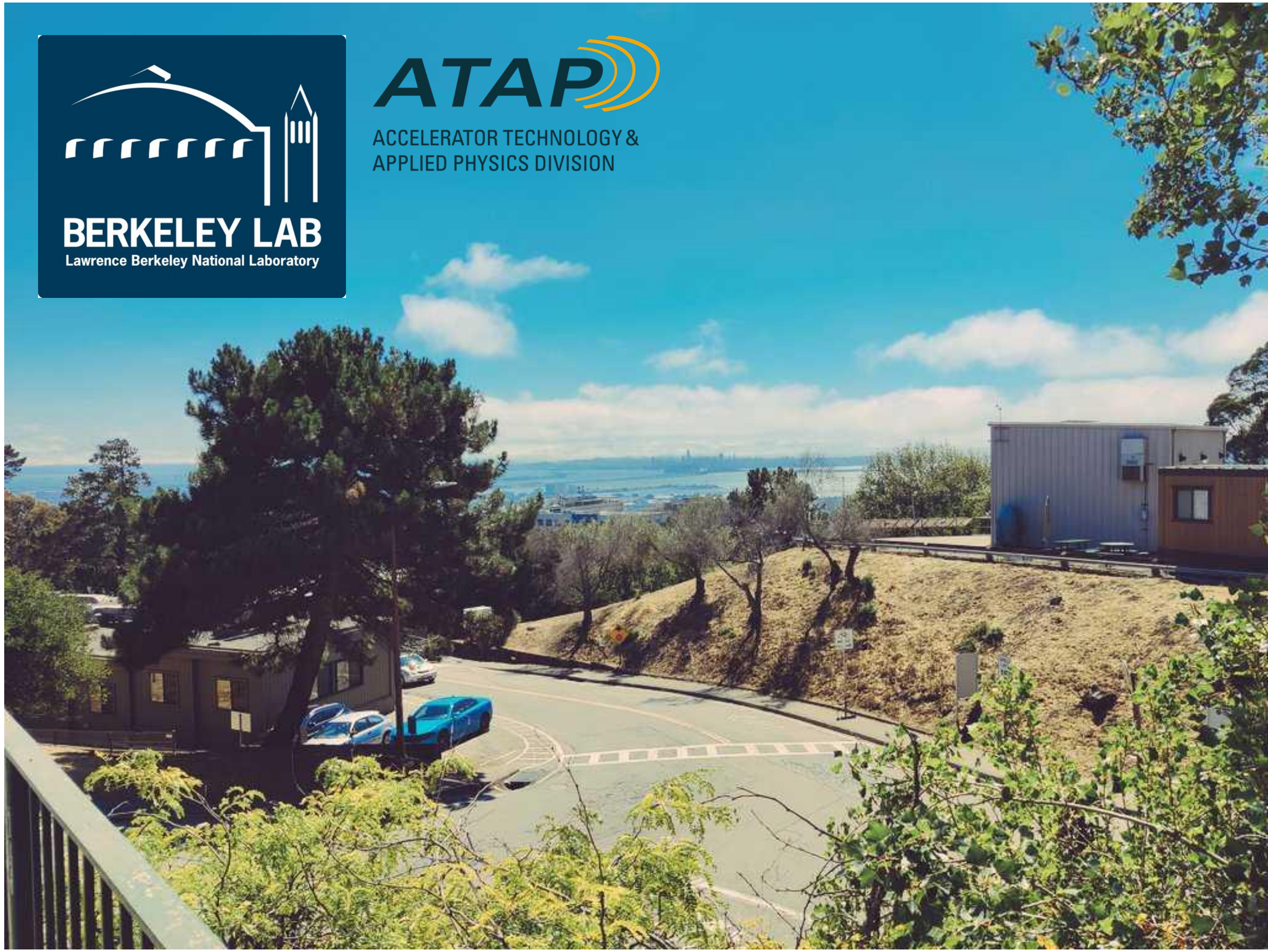
- **Modeling & Theory**
  - Exascale & Wakefields #92244
  - Beam Dynamics & ML #96603
- **Experiment**
  - Wakefields, kHz-MHz (LPA) #96321 #93729
  - Laser-Proton/Ion (LPI) #95498

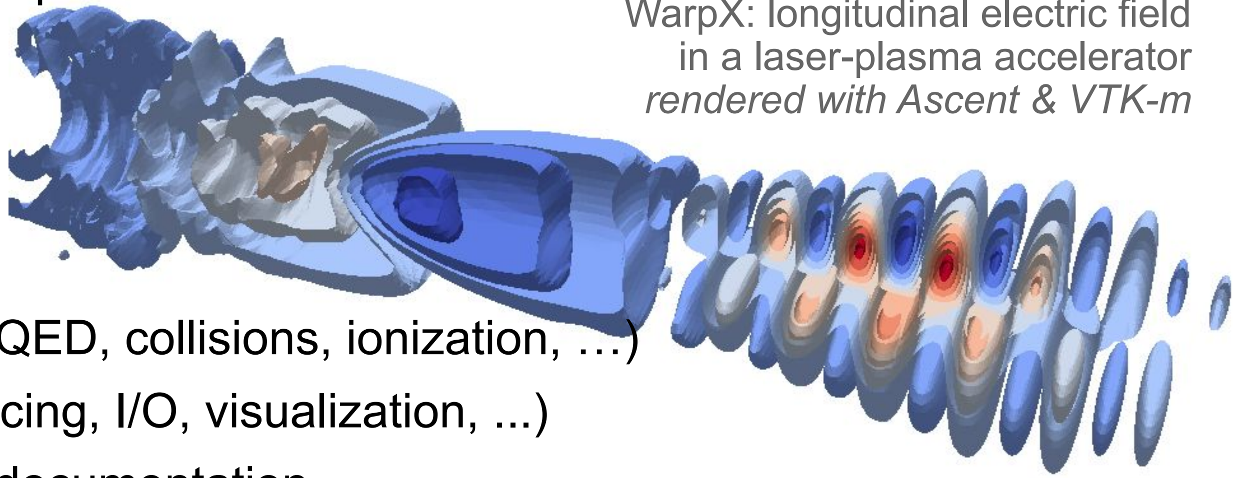


Summary

presented by: Axel Huebl (LBNL)
axelhuebl@lbl.gov

- **BLAST** is an open suite of PIC codes for **particle accelerator modeling**, increasingly build on top of the AMReX library, using code-sharing through the ABLASTR library and leveraging the U.S. DOE Exascale software stack. **ECP WarpX** is our first Exascale app, for relativistic plasma & beam modeling; **ImpactX** enhances these developments with AI/ML for s-based beam dynamics.

- **AMReX** for CPU/GPU Mesh-Refinement**, ABLASTR** shares PIC methods
  - Portable CPU/GPU frameworks that avoid code duplication
  - Efficient data structures, memory & comms.
  - Reuse numerical methods in various PIC loops
- **Vibrant Ecosystem and Contributions**
  - Runs on any platform: Linux, macOS, Windows
  - Specialized codes & advanced physics modules (QED, collisions, ionization, …)
  - Advanced computer science research (load-balancing, I/O, visualization, ...)
  - Public development, automated testing, review & documentation
  - Friendly, open & helpful community



WarpX: longitudinal electric field in a laser-plasma accelerator *rendered with Ascent & VTK-m*

github.com/ECP-WarpX

EXASCALE COMPUTING PROJECT
SciDAC Scientific Discovery through Advanced Computing
BERKELEY LAB LDRD