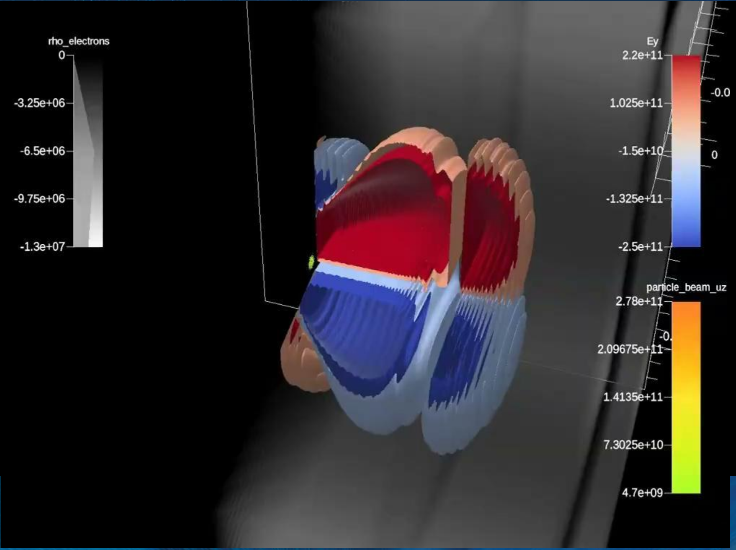
Simulations of Next-Generation Colliders

Axel Huebl, Remi Lehe, Ryan T Sandberg, Marco Garten, Arianna Formenti,
Olga Shapoval, Chad E Mitchell, Carlo Benedetti, and Jean-Luc Vay
Lawrence Berkeley National Laboratory



multi-stage LPA simulation in a
boosted frame with WarpX
transversely focusing fields & beam

Lisbon, March 19-22, 2024
5th ALEGRO (Advanced LinEar collider study GROup) Workshop

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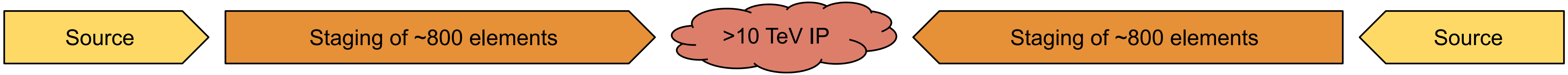
Simulations of Next-Generation Colliders



Algorithmic Options

From first principles to effective approximations and data models

Ecosystem of Simulation Codes

Collaboration for Advanced Modeling of Particle Accelerators

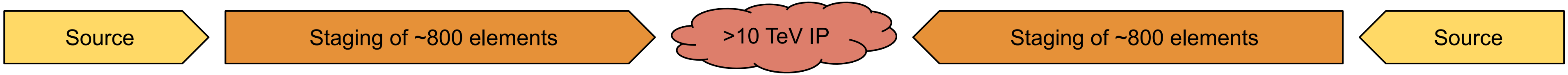
Modeling Staging: Levels of Realism

Number of stages modeled, plasma ramps, propagation & transport, more realistic beams, …

Algorithmic Options

From first principles to effective approximations and data models

General Algorithmic Choices



Speed

Fidelity

Fast

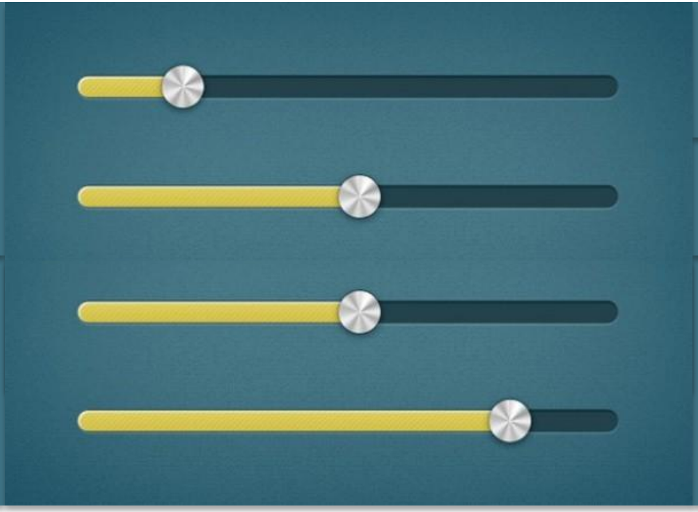
&

as

accurate

as

possible



Speed	Fidelity
Reduced physics	Full physics
Reduced models	First principles
1D-1V	3D-3V
Low resolution	High resolution

Accurate

&

as

fast

as

possible

e.g., initial designs, optimization & operations

e.g., stability proofs, exploration, ML training data

e.g., RZ geometry, quasi- and electro-static approximation, fluid background

This requires an **ecosystem of models**

⇒ share models & data between codes

⇒ works best when standardized

Algorithmic Options for Modeling Plasma Sources

Source | Staging of ~800 elements | >10 TeV IP | Staging of ~800 elements | Source

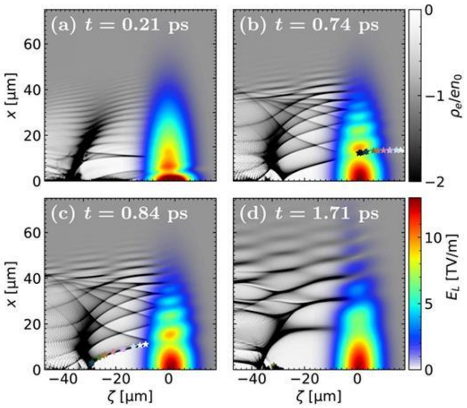
Generation
Full PIC in the lab frame or moderate boosted frame relativistic factor (e.g., γ=5)

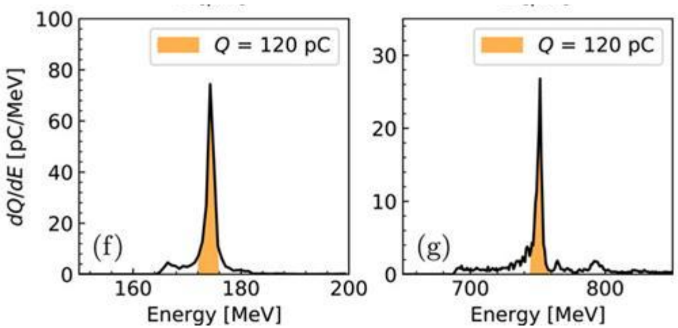
Physics at Play

- "high" energy spreads
- non-relativistic effects
- kinetics: wave breaking, self-injection, optical injection, ionization physics, …

Examples

injection induced by coaxial laser interference





WarpX

J Wang, M Zeng, D Li, X Wang, W Lu, J Gao,
“Injection induced by coaxial laser interference in laser wakefield accelerators”, Matter and Radiation at Extremes 7, 054001(2022)

Algorithmic Options for Modeling Plasma Sources

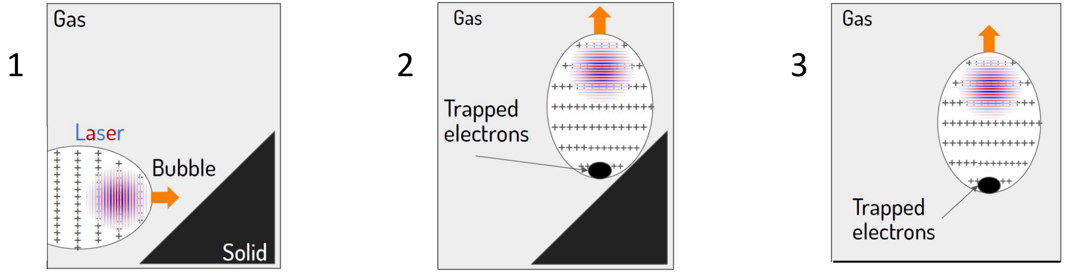
Generation
Full PIC in the lab frame or moderate boosted frame relativistic factor (e.g., γ=5)

Physics at Play

- "high" energy spreads
- non-relativistic effects
- laser-solid interaction

Examples

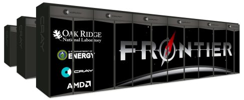
Two-stage injection+acceleration w/ plasma mirror

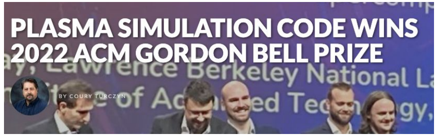


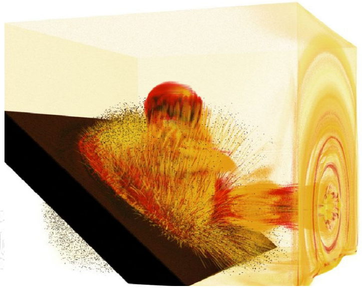
1st stage

Interaction with the plasma mirror

2nd stage



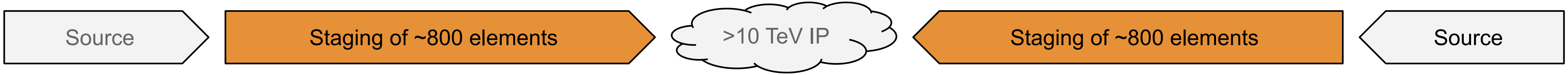

PLASMA SIMULATION CODE WINS 2022 ACM GORDON BELL PRIZE



WarpX

L Fedeli, A Huebl et al., SC22, ACM Gordon Bell Prize Winner (2022)

Algorithmic Options for Modeling Plasma Stages



Plasma Acceleration
Full PIC in high boosted frame relativistic factor (e.g., γ=60) or quasistatic

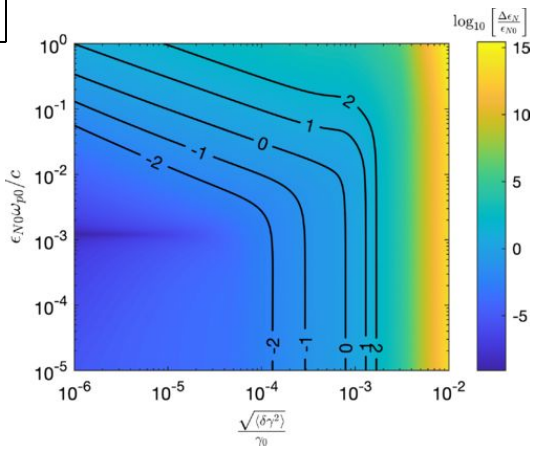
Talk yesterday by C. Benedetti

Physics at Play

- **driver and wakefield evolution**
- **beam loading**
- **phase mixing**
- **collisions with background plasma**
- **transverse stability**
- **transformer ratios**
- **coupling out of and into plasma ramps**
- **...**

Model assumption:
linear transport
no chromatic corrections
. . .

Severe energy spread restrictions?
dE/E<0.001



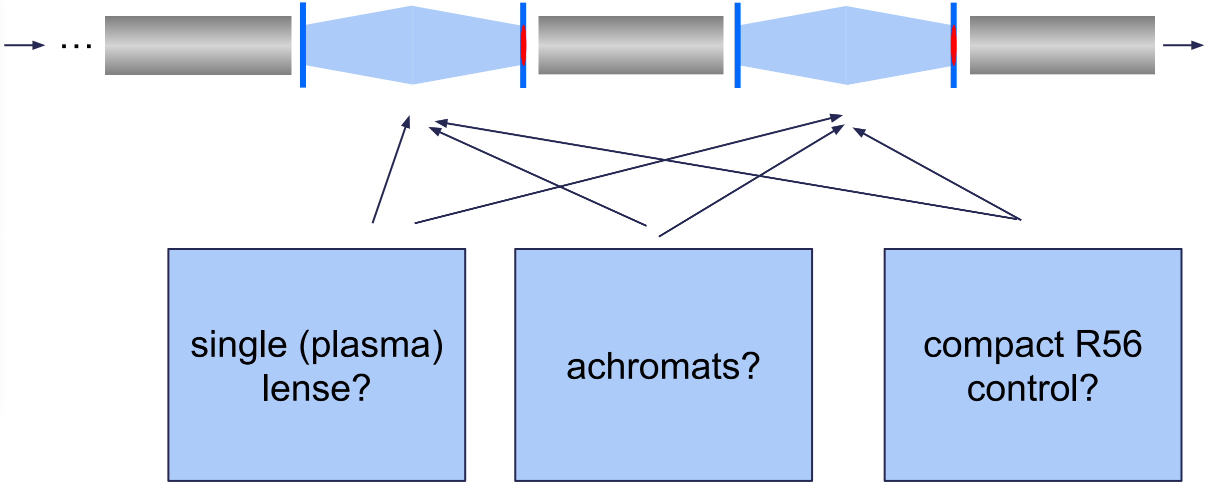
P5 Report: Exploring the Quantum Universe (2023); AGR Thomas and D Seipt, PRAB 24, 104602 (2021); B Foster et al., NJP 25,093037 (2023)
Schroeder et al, PRSTAB (2010); Schroeder et al., NIMA (2016); Benedetti et al., arXiv:2203.08366 (2022); Schroeder et al., JINST (2023)

Algorithmic Options for Modeling Transport Between Stages

Source → Staging of ~800 elements → >10 TeV IP ← Staging of ~800 elements ← Source

Plasma Acceleration
Full PIC in high boosted frame relativistic factor (e.g., γ=60) or quasistatic

Transport
Static PIC in beam-frame
t- or s-based



single (plasma) lense?

achromats?

compact R56 control?

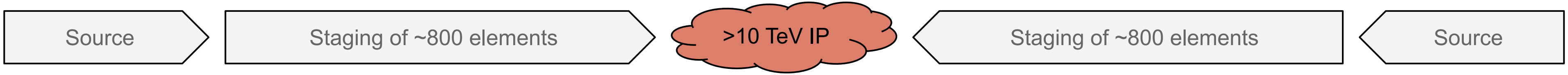
Scaling & compactness: early vs. mid vs late stages?

Physics at Play

- **energy spreads: dispersion, R_{56}**
- **beam matching**
- **space charge for >100pC charge**

CA Lindstrom and E Adli, PRAB 19, 071002 (2016)
A Huebl et al., NAPAC'22, DOI:10.18429/JACoW-NAPAC2022-TUYE2 (2022); A Huebl et al., AAC'22, in print, arXiv:2303.12873 (2022)

Algorithmic Options for the Interaction Point



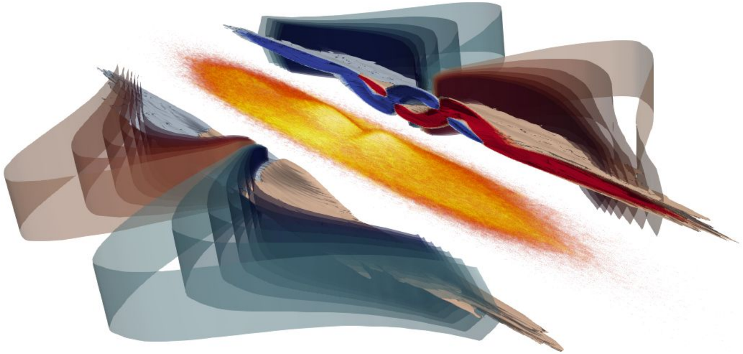
Source

Staging of ~800 elements

>10 TeV IP

Staging of ~800 elements

Source

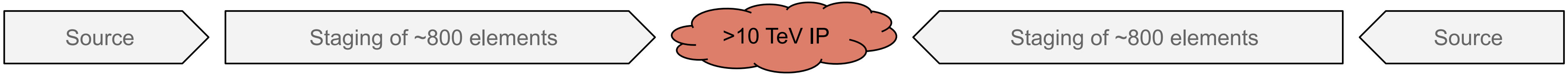


Beam Crossing
Full or static PIC in combination of beam & center of mass frames and Monte-Carlo QED

Physics at Play

- **disruption & beamstrahlung**
- **pair generation**
- **self-consistent pair plasmas**
- **hadron production**
- **crossing angles**

Algorithmic Options for the Interaction Point

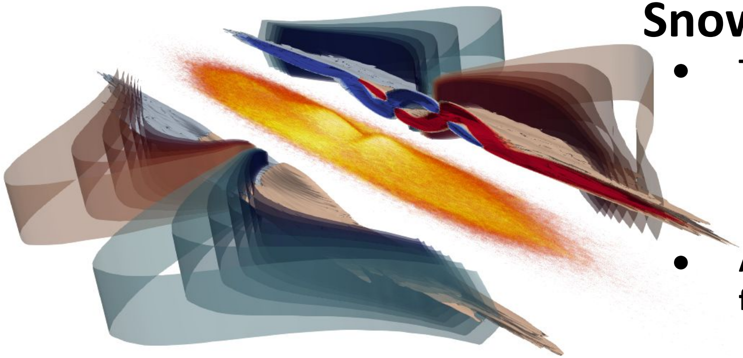

Source

Staging of ~800 elements

>10 TeV IP

Staging of ~800 elements

Source



Snowmass21: Beam-Beam Crossing Underexplored

- **There is long-standing skepticism that such a machine is possible:**
  - E.g., for e-/e+: "It is concluded that in the energy regime approaching 10 TeV the present single pass linear collider will probably be unsatisfactory due to high backgrounds, excessive power demand or both." [1]
- **A Beam-Beam Collaboration has formed motivated by design and simulation needs for a future 10 TeV pCM wakefield collider, as recommended in the 2023 P5 report**
  - T. Barklow, S. Gessner, M. Hogan, C.-K. Ng, D. Ntounis, M. Peskin, T. Raubenheimer, C. Vernieri, R. Watt (SLAC) - S. Bulanov, A. Formenti, R. Lehe, C. Schroeder, J.-L. Vay (LBNL) - W. Nguyen (Imperial College) - L. Fedeli, H. Vincenti (CEA Saclay) - G. Jiawei Cao, C. A. Lindstrøm (U. Oslo) - L. Gray (CERN)
- **The goals for this collaboration include:**
  - Understand the limitations of particle collisions at large beamstrahlung parameter.
  - Develop simulation tools that can accurately model these collisions.
  - Explore methods for suppressing (or embracing) beamstrahlung to enable high luminosity-per-power linear colliders.

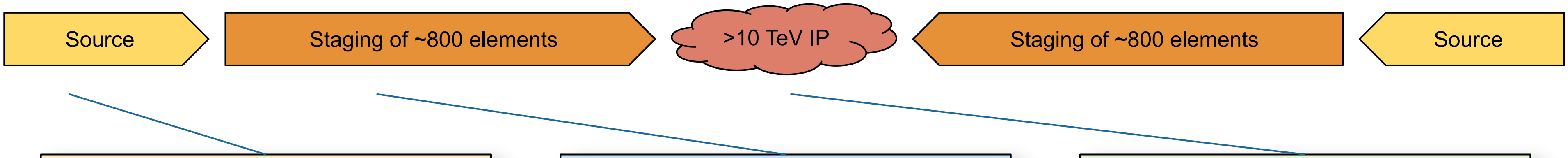
Physics at Play

- **disruption & beamstrahlung**
- **pair generation**
- **self-consistent pair plasmas**
- **hadron production**
- **crossing angles**

Snowmass 2021

P5 Report: Exploring the Quantum Universe (2023)
Barklow et al., JINST 18 P09022 (2023) DOI:10.1088/1748-0221/18/09/P09022; [1] M Tigner, AIP Conf. Proc. 279, 1–15 (1992) DOI:10.1063/1.44090

Algorithmic Options for Modeling the Whole Collider



Generation

Full PIC in the lab frame or moderate boosted frame relativistic factor (e.g., γ=5)

Plasma Acceleration

Full PIC in high boosted frame relativistic factor (e.g., γ=60) or quasistatic

Transport

Static PIC in beam-frame t- or s-based

Beam Crossing

Static PIC in combination of beam & center of mass frames and Monte-Carlo QED

Connections

- Record e^- and e^+ beams (and fields if transition within a stage) histories at a given location.
- Inject beams in next simulation; if within a stage, inject fields using a virtual antenna.

A Huebl et al., *openPMD*, DOI:10.5281/zenodo.591699 (2015); DP Grote et al., *Particle-In-Cell Modeling Interface (PICMI)* (2021); M. Thévenet et al., *LASY: an open-source Python library for easy interfacing of laser pulses between experiments and simulations*, EAAC23, under review (2023)

BLAST
BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

Developed by an international, multidisciplinary team

forming open governance

open source initiative®

THE LINUX FOUNDATION

HIGH PERFORMANCE SOFTWARE FOUNDATION


Jean-Luc Vay


Ji Qiang


Arianna Formenti


Marco Garten


Axel Huebl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Lixin Ge

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DE LA RECHERCHE À L'INDUSTRIE
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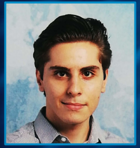
PARIS-SACLAY


Henri Vincenti


Luca Fedeli


Thomas Clark


Pierre Bartoli

CASUS
CENTER FOR ADVANCED SYSTEMS UNDERSTANDING


Franz Poeschel

tae TECHNOLOGIES


Roelof Groenewald

AVALANCHE

MODERN ELECTRON

***over 80* contributors, incl. from the private sector**

WarpX is a GPU-Accelerated PIC Code for Exascale

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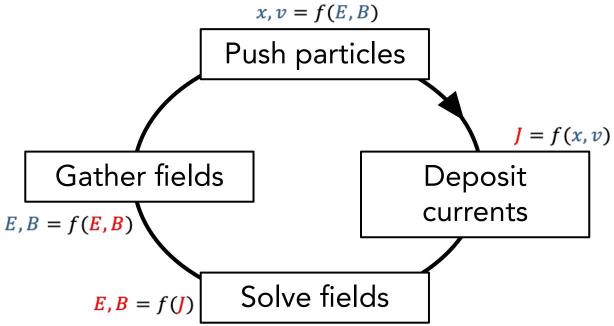
Multiple Particle-in-Cell Loops

- electromagnetic or -static (time integration)



$x, v = f(E, B)$

Push particles

$J = f(x, v)$

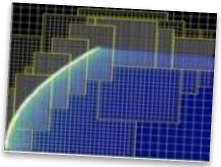
Deposit currents

$E, B = f(J)$

Solve fields

$E, B = f(E, B)$

Gather fields



Advanced algorithms

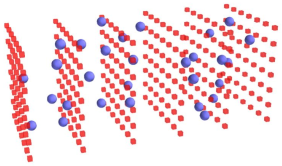
boosted frame, spectral solvers, Galilean frame, embedded boundaries + CAD, MR, …

Multi-Physics Modules

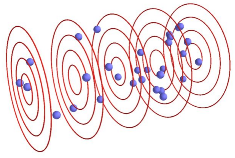
field ionization of atomic levels, Coulomb collisions, QED processes (e.g. pair creation), macroscopic materials, secondary emission

Geometries

- 1D3V, 2D3V, 3D3V and RZ (quasi-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 & Standardized

- PICMI input
- openPMD (HDF5 or ADIOS)
- in situ: diagnostics & Python APIs

EXASCALE COMPUTING PROJECT

SciDAC Scientific Discovery through Advanced Computing

L Fedeli, A Huebl et al., SC22, ACM Gordon Bell Prize Winner (2022)

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

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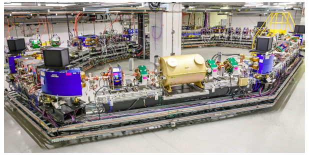
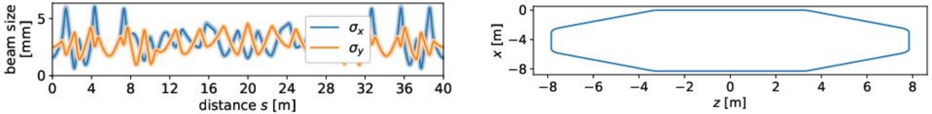
BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT



Particle-in-Cell Loop

- electrostatic
    - with space-charge effects
- s-based
    - relative to a reference particle
    - elements: symplectic maps

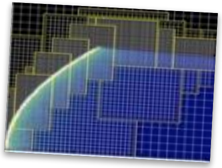


Fireproof Numerics

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

Triple Acceleration Approach

- GPU support
- Adaptive Mesh Refinement
- AI/ML & Data Driven Models



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SciDAC Scientific Discovery through Advanced Computing

A Huebl et al., NAPAC22 (2022)

User-Friendly

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

Multi-Node parallelization

- MPI: domain decomposition
- dynamic load balancing (in dev.)

On-Node Parallelization

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

mac OS

Scalable & Standardized

- openPMD (HDF5 or ADIOS)
- in situ: diagnostics & Python APIs

CAMPA

Collaboration for Advanced Modeling of Particle Accelerators

Collaboration for Advanced Modeling of Particle Accelerators

Fermilab

SLAC NATIONAL ACCELERATOR LABORATORY

BERKELEY LAB
Lawrence Berkeley National Laboratory

CAMPA

UCLA

Argonne NATIONAL LABORATORY

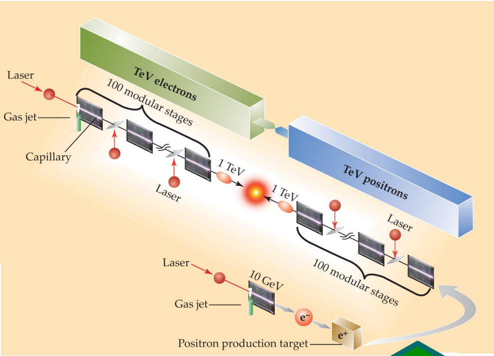
OAK RIDGE National Laboratory

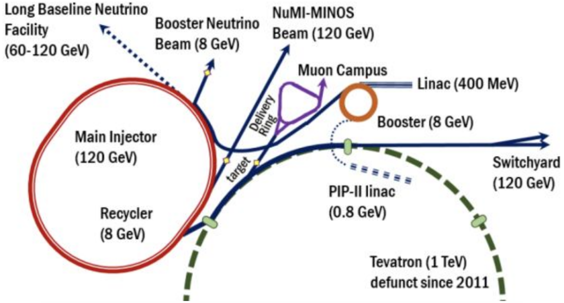
SciDAC
Scientific Discovery through Advanced Computing

ENERGY Office of Science

CAMPA is to boost accelerator research & designs

Overarching purpose of CAMPA: accelerate and expand the scope of discoveries from high energy physics (HEP) particle accelerators by enabling the design of accelerators that are significantly more compact and cheaper to build and run



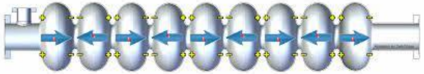


Emphasis: design of advanced plasma-based colliders and the conventional accelerators in the Fermilab complex, enabling DUNE to access previously unreachable parameters of the Standard Model neutrino sector

Main goals:

(i) develop **HPC accelerator & beam modeling capabilities** to **design the full range** of systems required

(ii) develop **community simulation ecosystems** that seamlessly **integrate accelerator elements** to facilitate the **design and control** of the next-generation of particle accelerators

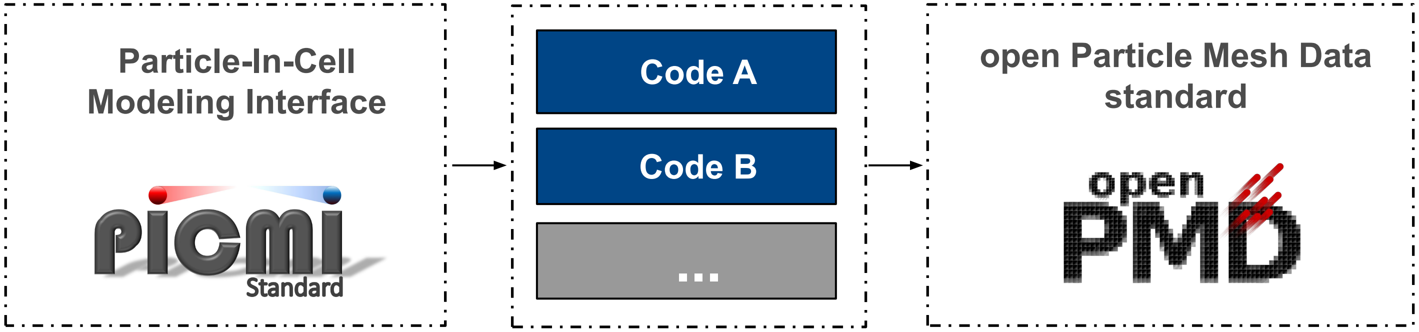


RF cavities in metallic vacuum tube
- gradient constrained by breakdown < 100 MV

Very synergistic with ALEGRO

Community Accelerator Simulations Ecosystem (CASE)

C A S E



Particle-In-Cell Modeling Interface

PICMI Standard

Code A

Code B

...

open Particle Mesh Data standard

openPMD

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plasmapy

MAISON DE LA SIMULATION

CAMPA Supported Application Software

BLAST BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

2D-RZ
- **Wake-T[1,2]**
- **FBPIC[2]**

3D
- **HiPACE++[2]**
- **ImpactX[1]**
- **WarpX[1,2]**

UCLA

2D-RZ
- **QPAD[2]**

3D
- **QuickPIC[2]**
- **OSIRIS[2]**

Fermilab

3D
- **Synergia[1]**

[1] Conventional accelerators

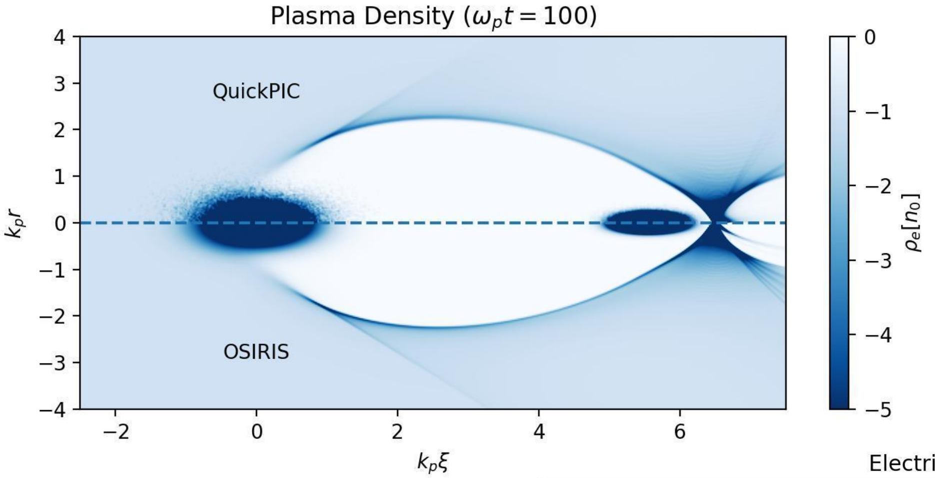
[2] Plasma-based accelerators

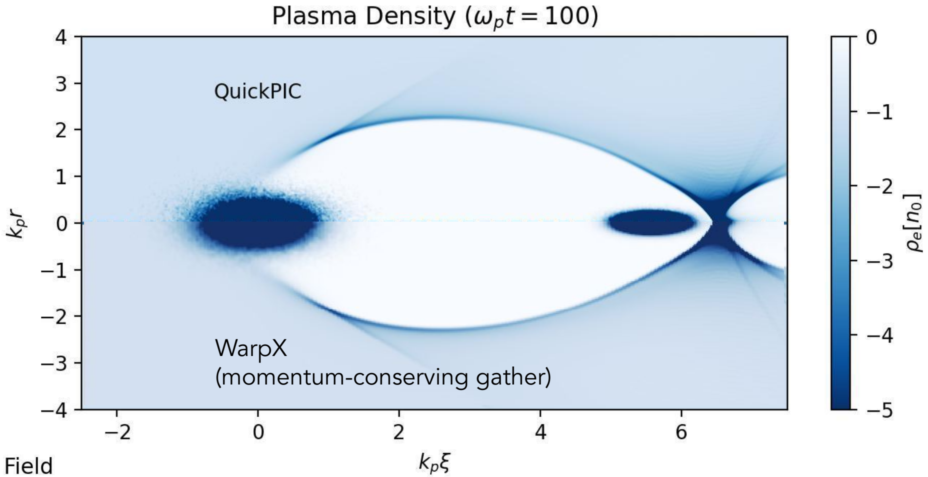
LASY

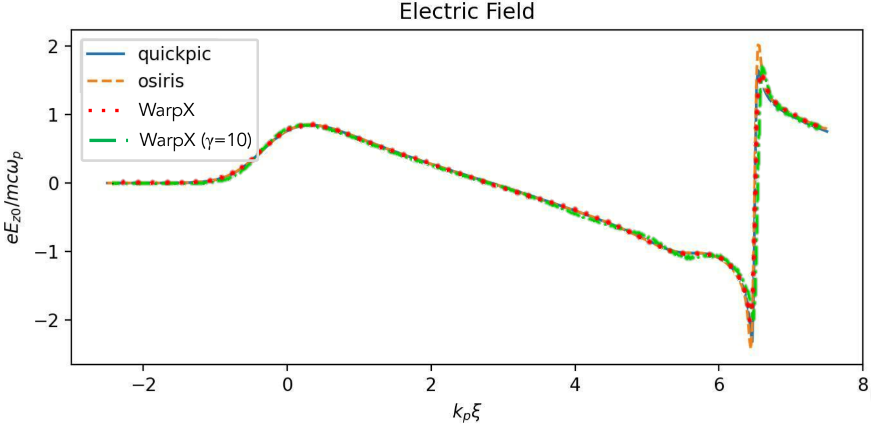
optimas

A Huebl et al., DOI:10.5281/zenodo.591699 (2015); DP Grote et al., *Particle-In-Cell Modeling Interface (PICMI)* (2021); LD Amorim et al., *GPos* (2021); M Thévenet et al., EAAC23, arXiv:2403.12191 (2023); A Ferran Pousa et al., DOI:10.5281/zenodo.7989119 (2023); RT Sandberg et al., IPAC23, DOI:10.18429/JACoW-IPAC-23-WEPA101 (2023)

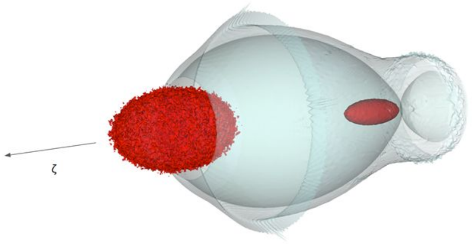
PICMI enables (90%) same input script with different codes







PWFA FACET Example



PICMI
Standard

Modeling Staging: Levels of Realism

number of stages modeled, plasma ramps, propagation & transport, realistic beams, …

Systematically Increasing the Realism for Start-to-End Modeling

Start-to-End Physics Goals

The HEP community expects us to prove our machines in high-fidelity modeling **robust start-to-end designs**.

- Maximize **energy gain** & conserve **charge transport**
  - plasma profile/channel design
  - matching into plasma stages
  - transverse beam stability
- Minimize **energy spread**
  - Requires flattening of wakefield over LPA length → bunch current profile
- Minimize **Emittance** growth, e.g.,
  - low phase mixing from energy-spread + betatron motion,
  - controlled beam expansion at plasma exit
  - reduce collision with background plasma, …
- **Compactness** and **energy efficiency**
  - What is the best transport on a realistic **length scale** that allows for beam exit, coupling in a new laser pulse, beam matching to a new stage
- **Robustness**: realistic fluctuations & uncertainties in ops.

Modeling Capability & Workflow Needs

The community started with **exploratory LPA elements**, it is time to expand and model their interplay with and operation in beamlines that are **available now and in the next decade**.

- **Codes**: start w/ speed, then proof in high fidelity

- Exploration and **optimization workflows**: parameters can depend on previous stage
  - Single stage design
  - Transport design
  - Multi-stage design

optimas

⇒ ***reproduce, automate & repeat, memorize (ML), abstract away***

- Systematically **removing idealizations**
  - laser profiles & coupling,
  - realistic beam (charge, profile, spreads),
  - transport distances, …

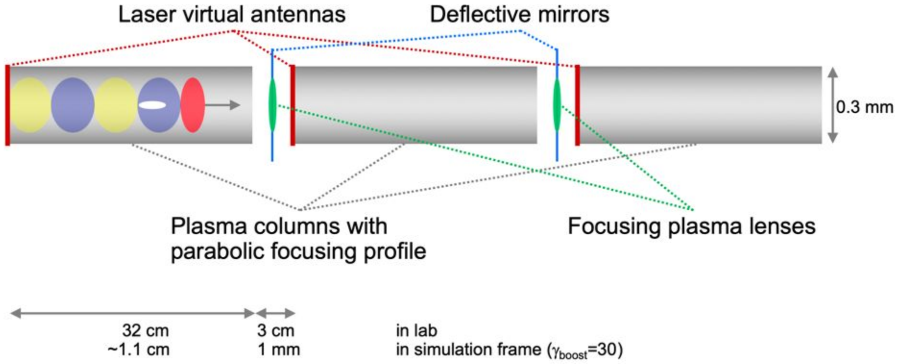
LASY

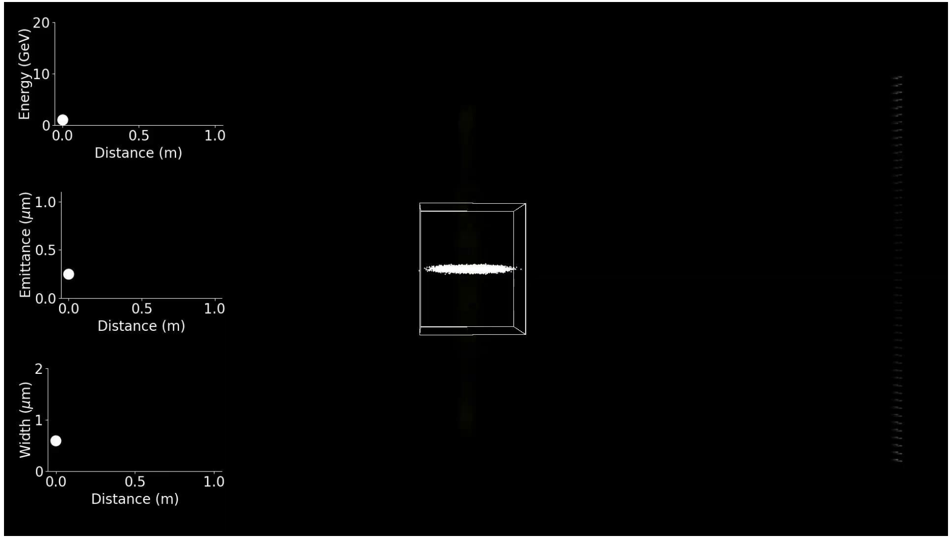
P5 Report: Exploring the Quantum Universe (2023); AGR Thomas and D Seipt, PRAB 24, 104602 (2021); M Thévenet et al., EAAC23, arXiv:2403.12191 (2023); Schroeder et al, PRSTAB (2010); Schroeder et al., NIMA (2016); Benedetti et al., arXiv:2203.08366 (2022); Schroeder et al., JINST (2023)

Level of Realism: 3 multi-GeV Stages Modeled in 3D

Source → Staging of ~800 elements → >10 TeV IP ← Staging of ~800 elements ← Source

Plasma lenses to focus e$^-$ beam between stages





Movie from boosted frame data. Aspect ratio different from lab.

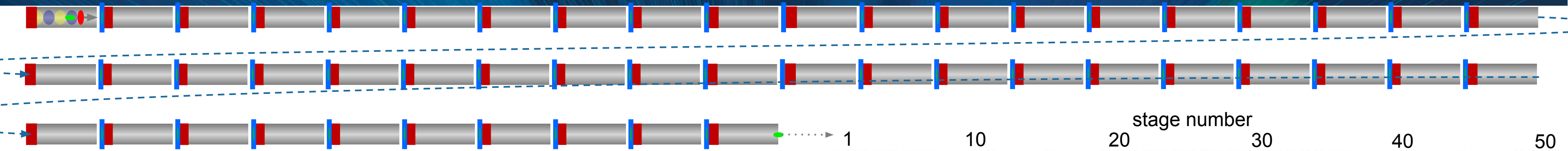
Focus was on numerics: performance, numerical convergence, etc.

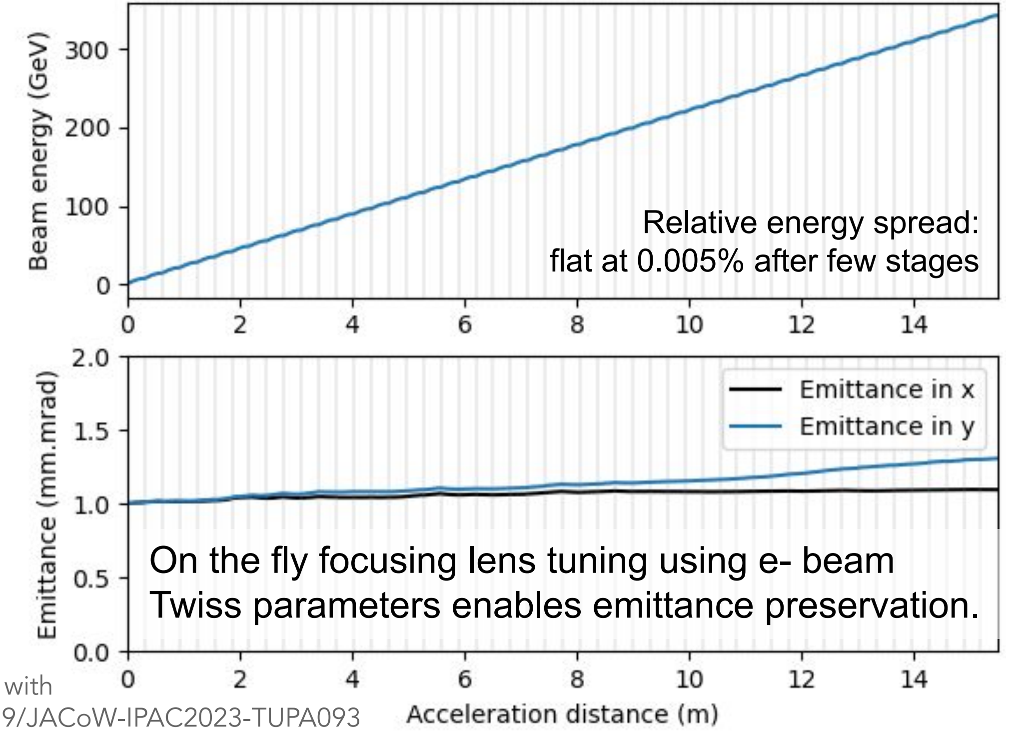
WarpX

Focus was not on science, e.g., emittance preservation ⇒ some tuning of plasma lens amplitude performed but not optimized.

Video: M Thévent et al. (2019); J-L Vay et al., EAAC2019 (2019); J-L Vay, A Huebl et al., Phys. Plasmas 28, 023105 (2021) DOI:10.1063/5.0028512

Level of Realism: 50 multi-GeV Stages Modeled in 3D





Relative energy spread: flat at 0.005% after few stages

On the fly focusing lens tuning using e- beam Twiss parameters enables emittance preservation.

LWFA lattice:

- Plasma channels: 28cm
- Gaps: 3cm
- Plasma lens model: linear thick lens (3 mm) w/ “residence correction”

Electron beam:

- Charge: -1 fC
- Size: 0.75 μm x 0.75 μm x 0.1 μm
- Emittance: 1 mm.mrad

WarpX

Grid size/resolution:

- 128 x 128 x 17664, boosted frame
- 2 μm x 2 μm x 0.01 μm

Computer: 256 GPUs for 8h on Perlmutter (NERSC)

J-L Vay et al., WarpX MS FY23.1 and FY23.2 (2023); work in collaboration with A Ferran Pousa (DESY); A Ferran Pousa et al., IPAC23 (2023) DOI:10.18429/JACoW-IPAC2023-TUPA093

Emittance Preservation for Plasma-Vacuum Coupling

Source → Staging of ~800 elements → >10 TeV IP ← Staging of ~800 elements ← Source

What is the best exit ramp shape?

- Tested two ramp shapes (one reduces to the other)
- Density bump was suggested to reduce divergence after beam expansion in ramp

Emittance growth from chromaticity in drifts:

$$\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}$$

Exit ramp expands the beam: ε_0/σ_0 decreases!

P. Antici et al., JAP (2012)
M. Migliorati et al., PRAB (2013)

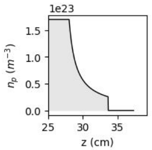
Objective: minimize emittance growth
Via Bayesian Optimization

$$f = \lg\left(\frac{\bar{\epsilon}_n - \bar{\epsilon}_{n,0}}{\bar{\epsilon}_{n,0}}\right), \qquad \bar{\epsilon}_n = \sqrt{\epsilon_{n,x}\cdot\epsilon_{n,y}}$$

after 28 cm plasma stage, 9.33 cm downramp, 1m drift, $\epsilon_{n,0}$ = 1 µm

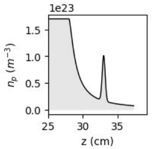
A) 2 parameters

$$n_e = \frac{1}{1+\frac{z}{L_d}}, \qquad n_e < n_{\text{cutoff}} = 0$$



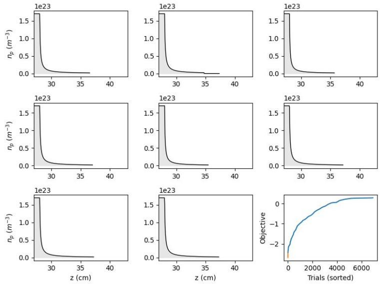
B) 5 parameters

$$n_e = \frac{1}{1+(\frac{z}{L_d})^c} + h\cdot\exp\left(-\frac{(z-z_b)^2}{w^2}\right)$$

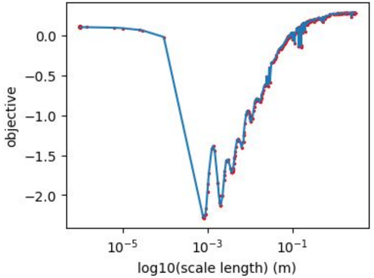


Results

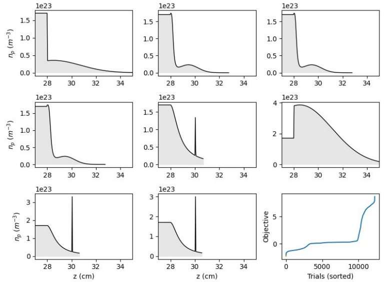
6912 runs $\Delta\epsilon$ < 3 nm



Emittance growth dependency on scale length



12240 runs $\Delta\epsilon$ < 6 nm



- Very good emittance preservation: $\Delta\epsilon$ < 3 nm (1st stage)
- Best emittance with optimized shape (A)
- We do not yet converge from (B) to (A)

Emittance Preservation for Plasma-Vacuum Coupling

Optimized Emittance: Stages at GeV…TeV Range

E_0	**1 GeV**	**10 GeV**	**100 GeV**	**1 TeV**	**10 TeV**
$\Delta\epsilon/\epsilon$	0.3%	3.0%	0.4%	1e-6	1e-6
$\Delta\epsilon/\epsilon$ (10 pC & 0.5% $\Delta E/E_0$)	0.5%	3.6%	1.3%	0.1%	0.2%

Emittance growth from chromaticity in drifts:

$$\boxed{\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}}$$

Exit ramp expands the beam: ε_0/σ_0 decreases!

P. Antici et al., JAP (2012)
M. Migliorati et al., PRAB (2013)

$$\lambda_\beta \propto \sqrt{\frac{2\gamma}{n_e}}$$

Betatron wavelength
Appropriate length scale increases with energy but emittance growth is also reduced

> According to this preliminary RZ study, if we controllably expand the beam in the plasma ramp, **adiabatic matching** of the ramps L~√γ **might not be needed**!

Density Ramps: Next Steps

- Redo scans **with beam loading** (100s of pC)
- Reproduce emittance preservation in **high fidelity** (3D WarpX)
- Try other optimizers to explore minima

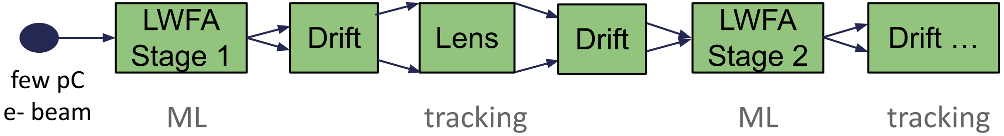
Associated Challenges

- **Current profiles** for flattened wakefield require **additional optimization** for every stage
- 3D simulations demand more resources (model ion motion → suppress hosing for high-charge, low-emittance beams)

WakeT
optimas
libEnsemble

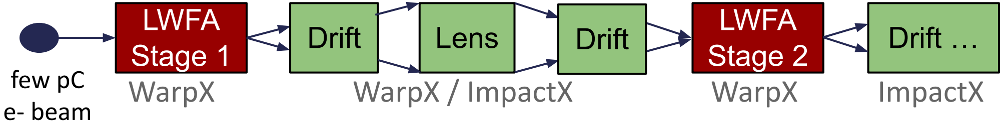
Modeling of Propagation & Transport

ML boosted: for a *specific* problem


LWFA Stage 1
Drift
Lens
Drift
LWFA Stage 2
Drift …
few pC e- beam
ML
tracking
ML
tracking

- start-to-end collider modeling
- digital twin / ‘real-time’

Model Speed: for accelerator elements


LWFA Stage 1
Drift
Lens
Drift
LWFA Stage 2
Drift …
few pC e- beam
WarpX
WarpX / ImpactX
WarpX
ImpactX

Simulation time: full geometry, full physics

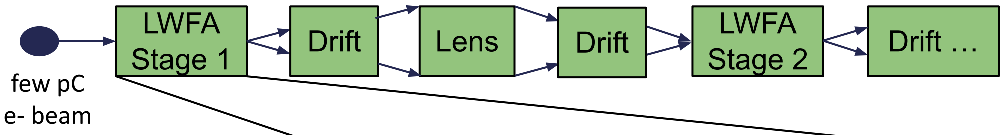
5 hrs
256 GPUs

<sec
1 GPU

WarpX

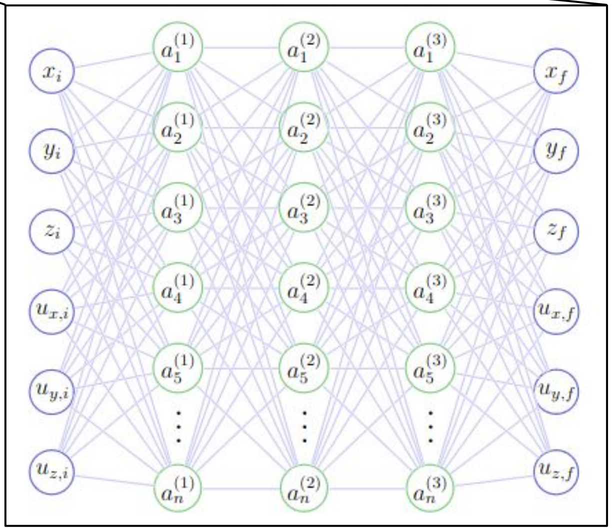
RT Sandberg et al. and A Huebl, *accepted to PASC24*, arXiv:2402.17248 (2024)
RT Sandberg et al and A Huebl, IPAC23, DOI:10.18429/JACoW-IPAC-23-WEPA101 (2023)

We Trained a Neural Net with WarpX for Staging of Electrons



few pC
e- beam

LWFA Stage 1 → Drift → Lens → Drift → LWFA Stage 2 → Drift …

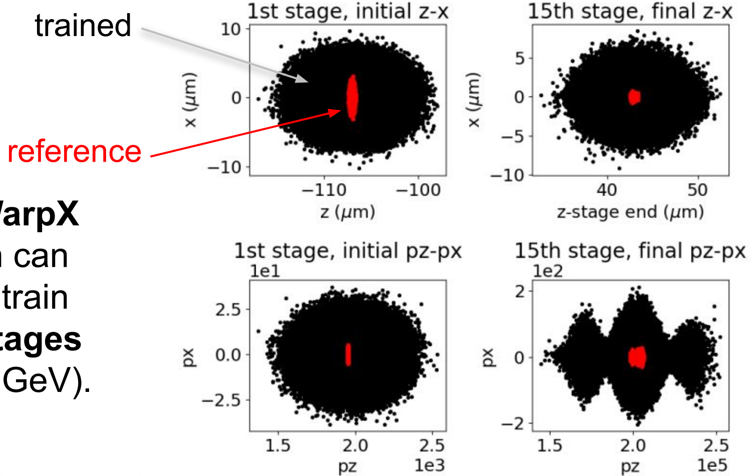


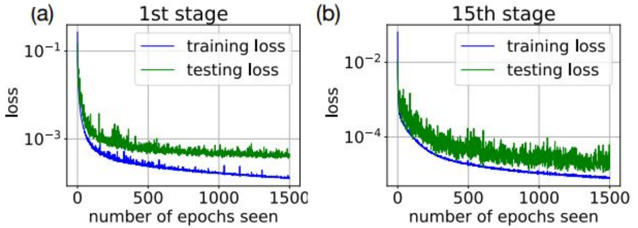
A Neural Net is a non-linear transfer map!

Assumption: purely tracking

A **single WarpX simulation** can be used to train **multiple stages** (7,14,21,…GeV).

openPMD PyTorch





Hyperparameters

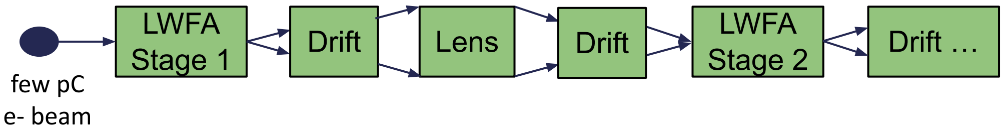
- 6D in 6D out
- 3-5 hidden layers with 700-900 nodes each are sufficient

Training data: 1M particles / beam
Training time: 2-2.2 hrs on 1 GPU

WarpX

RT Sandberg et al. and A Huebl, *accepted to PASC24*, arXiv:2402.17248 (2024)
RT Sandberg et al and A Huebl, IPAC23, DOI:10.18429/JACoW-IPAC-23-WEPA101 (2023)

Modeling + ML Inference are Fully GPU Accelerated

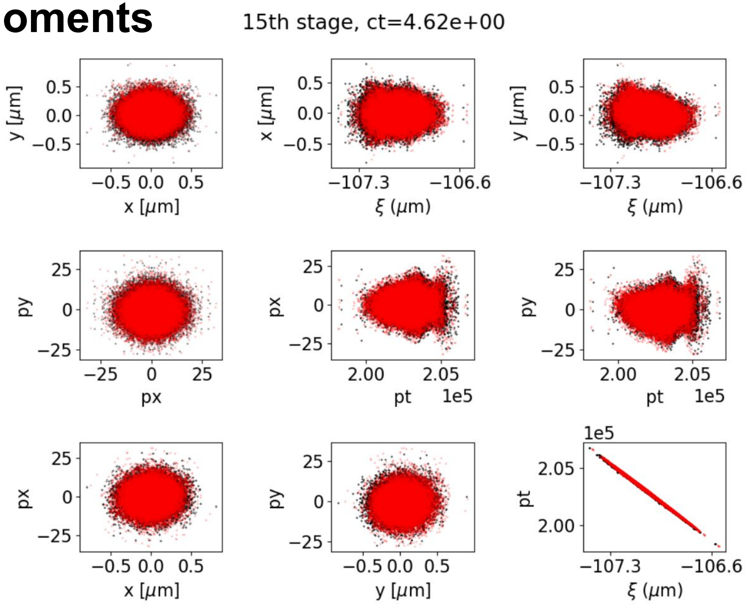


few pC
e- beam

LWFA Stage 1 → Drift → Lens → Drift → LWFA Stage 2 → Drift …

Predictive Quality Test: Error in Beam Moments

	stage 1	**stage 2**	**stage 15**
$\boldsymbol{\sigma_x}$	0.12%	1.8%	3.2%
$\boldsymbol{\sigma_{px}}$	0.54%	2.1%	2.8%
$\boldsymbol{\varepsilon_x}$	0.43%	0.38%	0.39%
$\boldsymbol{\sigma_y}$	0.03%	1.5%	1.2%
$\boldsymbol{\sigma_{py}}$	0.3%	1.9%	3.2%
$\boldsymbol{\varepsilon_y}$	0.3%	0.44%	2.1%


15th stage, ct=4.62e+00

Training data: 1M particles / beam
Training time: 2-2.2 hrs on 1 GPU

ImpactX

RT Sandberg et al. and A Huebl, *accepted to PASC24*, arXiv:2402.17248 (2024)
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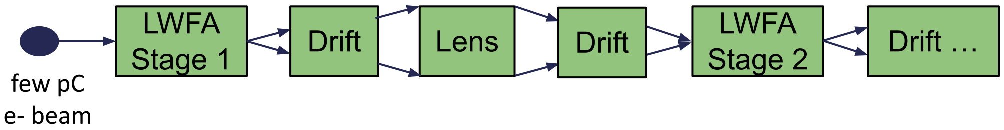
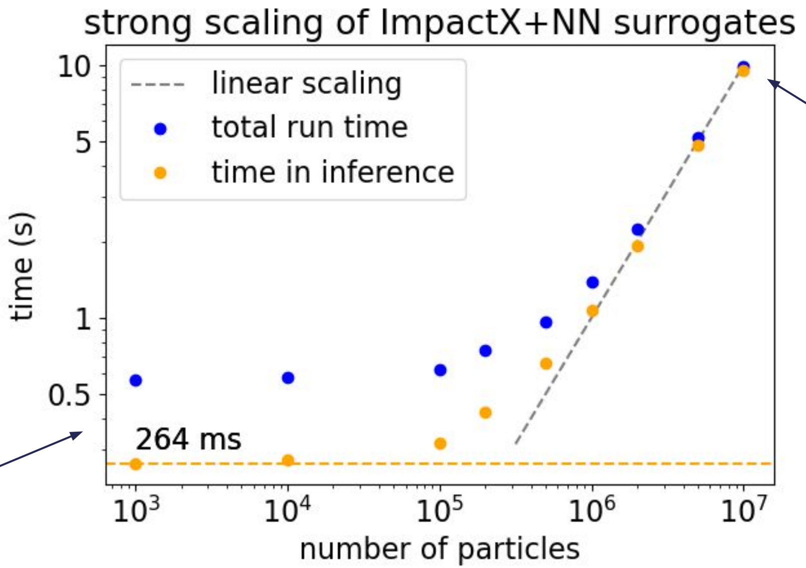


GPU inference time: 63ns / particle / stage
ImpactX tracking >1M particles



ImpactX: 10 GPU sec
for 15 surrogates

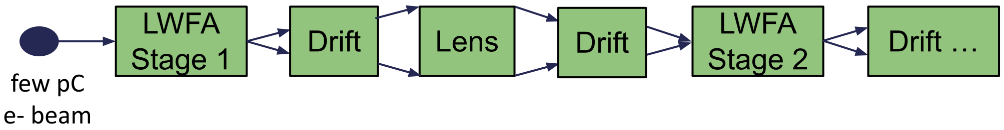
WarpX: 1,316 GPU hrs
15 stage reference
simulation

ImpactX, 1 GPU:
2-4 simulations / second!

ImpactX

RT Sandberg et al. and A Huebl, *accepted to PASC24*, arXiv:2402.17248 (2024)
RT Sandberg et al and A Huebl, IPAC23, DOI:10.18429/JACoW-IPAC-23-WEPA101 (2023)

Modeling + ML Inference: Rapid Start-to-End Optimization



few pC
e- beam

LWFA Stage 1

Drift

Lens

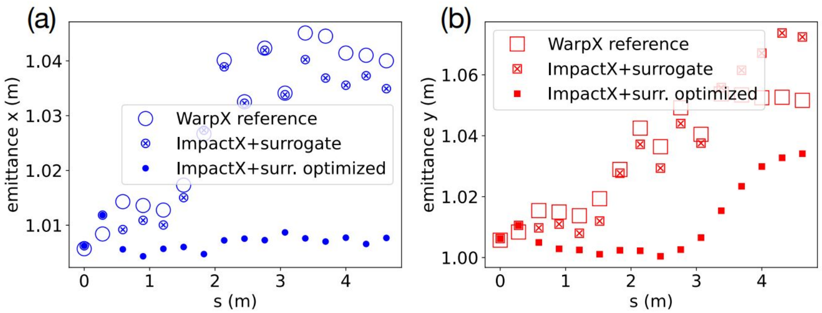
Drift

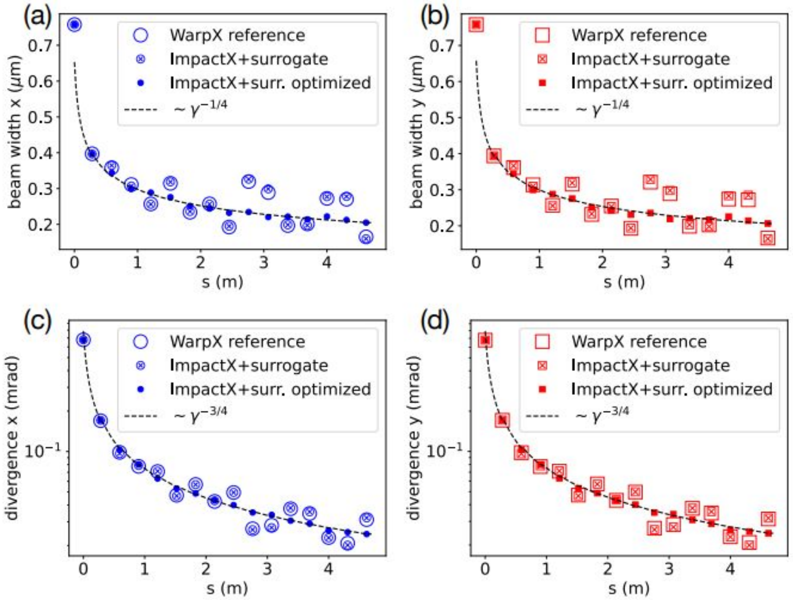
LWFA Stage 2

Drift …

GPU inference time: 63ns / particle / stage
ImpactX tracking >1M particles

Rapid Start-to-End Optimization for Transport Design





Crucial, Open Challenges

- microscopic *and* collective effects together: <u>space charge</u>
- better conserve <u>beam moments</u>

feedback & collabs wanted

ImpactX

RT Sandberg et al. and A Huebl, *accepted to PASC24*, arXiv:2402.17248 (2024)
RT Sandberg et al and A Huebl, IPAC23, DOI:10.18429/JACoW-IPAC-23-WEPA101 (2023)

Modeling + ML Inference: Enables Complex Transport Design Studies


Source

Staging of ~800 elements

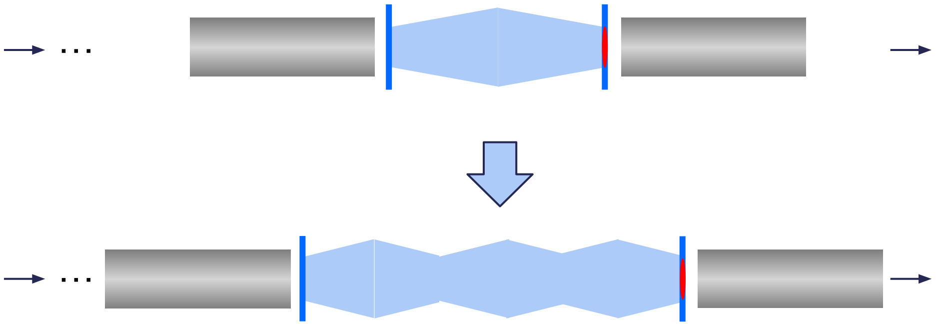
>10 TeV IP

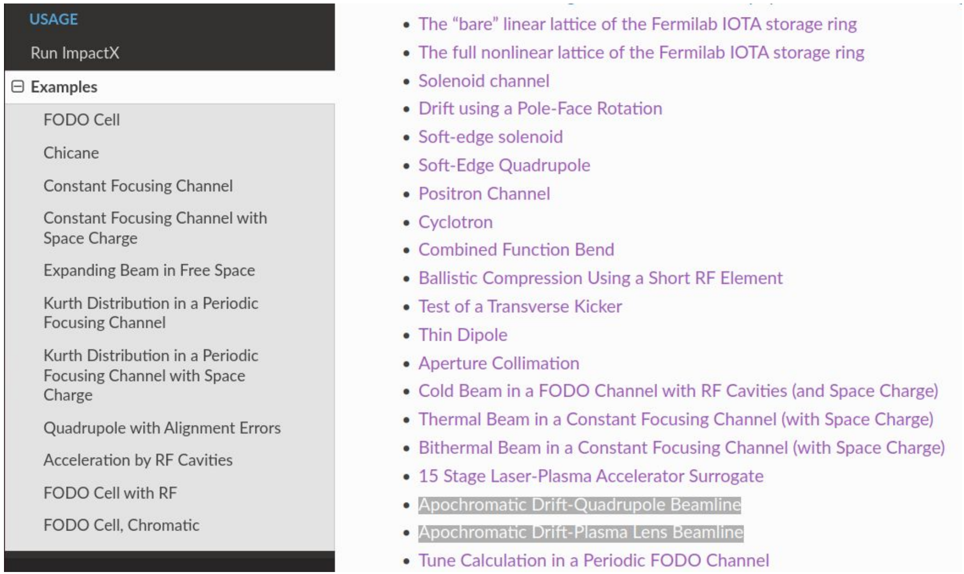
Staging of ~800 elements

Source

Next Step: Chromatic Corrections

- **Plasma lenses: simple to complex models**
- **Aprochomats: ready in ImpactX**
- **More compact solutions proposed by Lindstrøm et al.**



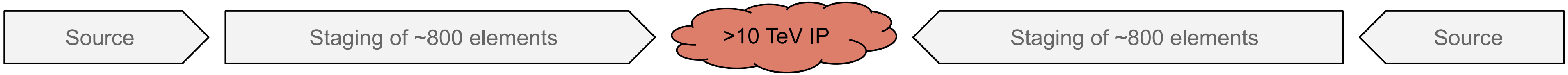


- The “bare” linear lattice of the Fermilab IOTA storage ring
- The full nonlinear lattice of the Fermilab IOTA storage ring
- Solenoid channel
- Drift using a Pole-Face Rotation
- Soft-edge solenoid
- Soft-Edge Quadrupole
- Positron Channel
- Cyclotron
- Combined Function Bend
- Ballistic Compression Using a Short RF Element
- Test of a Transverse Kicker
- Thin Dipole
- Aperture Collimation
- Cold Beam in a FODO Channel with RF Cavities (and Space Charge)
- Thermal Beam in a Constant Focusing Channel (with Space Charge)
- Bithermal Beam in a Constant Focusing Channel (with Space Charge)
- 15 Stage Laser-Plasma Accelerator Surrogate
- Apochromatic Drift-Quadrupole Beamline
- Apochromatic Drift-Plasma Lens Beamline
- Tune Calculation in a Periodic FODO Channel

CA Lindstrøm and E Adli, PRAB 19, 071002 (2016); A Huebl et al., NAPAC'22, DOI:10.18429/JACoW-NAPAC2022-TUYE2 (2022); A Huebl et al., AAC’22, in print, arXiv:2303.12873 (2022); RT Sandberg et al. and A Huebl, accepted to PASC24, arXiv:2402.17248 (2024)

github.com/**ECP-WarpX/impactx**

Model Level of Realism: Benchmarking Interaction Point Physics

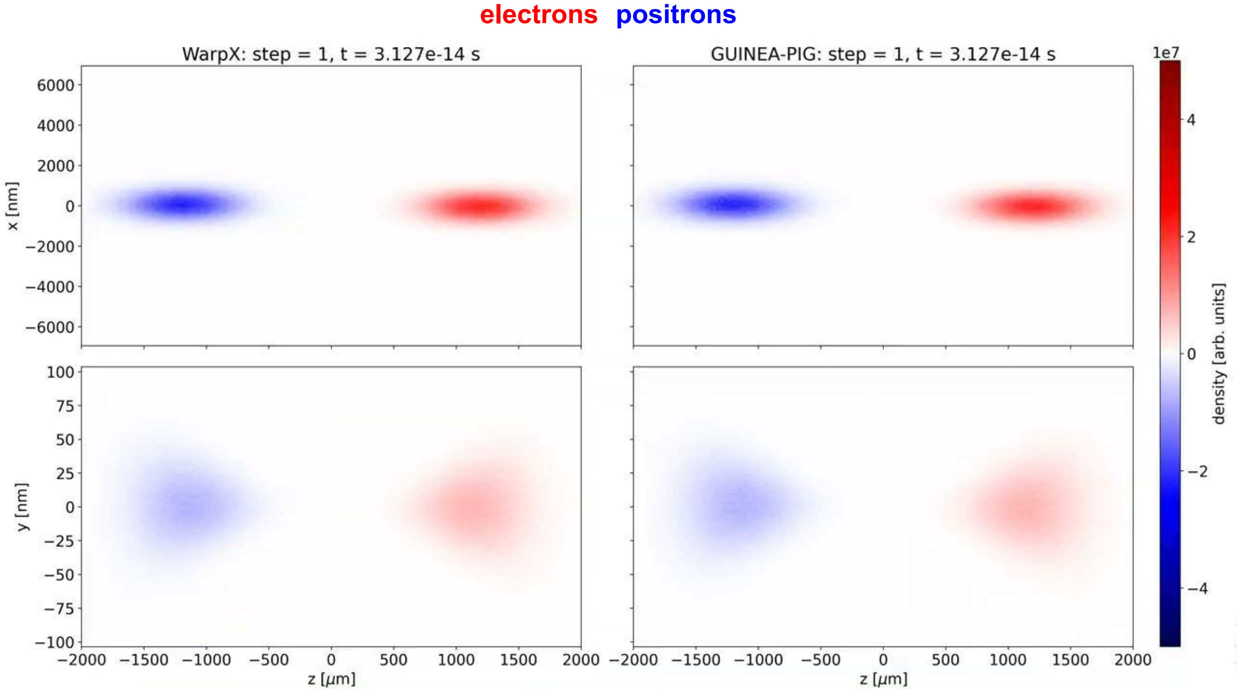

Source → Staging of ~800 elements → >10 TeV IP ← Staging of ~800 elements ← Source

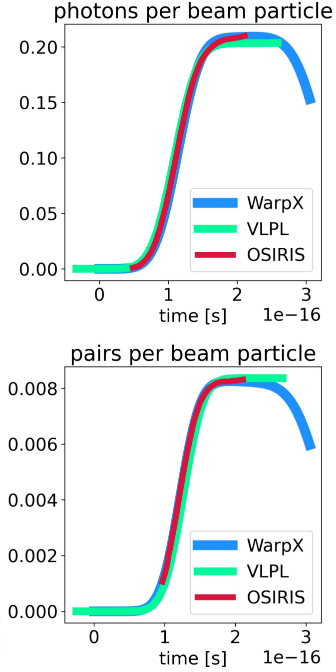
Flat ILC Beams 250 GeV COM*
- high beam disruption
- no significant pair creation

WarpX

*We also tested: **spherical, round and asymmetric beams** incl. HALHF parameters

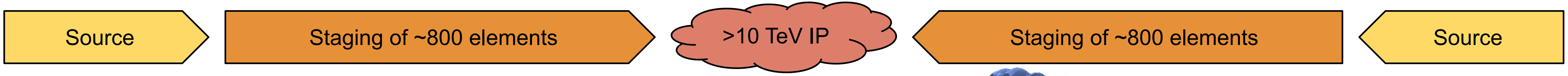
Spherical ~nm beams
- low beam disruption
- significant pair creation





Yakimenko et al., PRL (2019)

Summary



Algorithmic Options

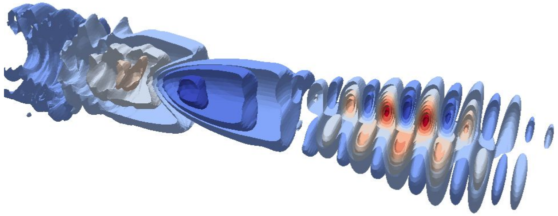
- particle-in-cell codes for plasma and transport
- Different **levels of fidelity** for different purposes: initial design, exploration, stability & scalability proof, start-to-end design, …

Community Ecosystems

- Modeling **must go through all stages of demonstration**, reduced to high-fidelity, so our designs can be taken seriously by the HEP community.
- **Compatibility** (data/input) between codes is important: benchmarks & rapid collider design iterations are needed!

Levels of Realism for Staging

- Progress: 3D (50 stages, TeV level), need 10x for new CoM goals
  - Good e- progress, more optimization & realism potential
- Transport designs: active - can we find compact solutions?
- IP & sources: use Exascale codes - exploration ongoing



Start-to-End: Community Codes

- Developed openly, well-documented, standardized
- Feature-rich: many algorithms
- Continuously benchmarked
- GPU-accelerated options (Nvidia/AMD/Intel)
- Scalable: desktop study to HPC

github.com/**ECP-WarpX**
github.com/**Hi-PACE**
github.com/**openPMD** **www.openPMD.org**
github.com/**AMReX-Codes**
github.com/**picmi-standard**
github.com/**UCLA-Plasma-Simulation-Group**
github.com/**fnalacceleratormodeling**

Contacts & Funding Acknowledgements

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CAMPA Project (SciDAC-HEP)

- PI: Jean-Luc Vay, jlvay@lbl.gov
- campa.lbl.gov, blast.lbl.gov

open source initiative®

github.com/**ECP-WarpX**
github.com/**Hi-PACE**
github.com/**openPMD** **www.openPMD.org**
github.com/**AMReX-Codes**
github.com/**picmi-standard**
github.com/**UCLA-Plasma-Simulation-Group**
github.com/**fnalacceleratormodeling**

Fermilab SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB CAMPA UCLA
Argonne NATIONAL LABORATORY OAK RIDGE National Laboratory

This research was supported by the **Exascale Computing Project** (17-SC-20-SC), a collaborative effort of two **U.S. Department of Energy organizations (Office of Science and the National Nuclear Security Administration)** responsible for the planning and preparation of a capable exascale ecosystem, including software, applications, hardware, advanced system engineering and early testbed platforms, in support of the nation’s exascale computing imperative. This work was also performed in part by the **Laboratory Directed Research and Development Program of Lawrence Berkeley National Laboratory** under U.S. Department of Energy Contract No. DE-AC02-05CH11231, **Lawrence Livermore National Laboratory** under Contract No. DE-AC52–07NA27344 and **SLAC National Accelerator Laboratory** under Contract No. AC02–76SF00515. Supported by the **CAMPA collaboration**, a project of the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research and Office of High Energy Physics, **Scientific Discovery through Advanced Computing (SciDAC)** program. 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, and the supercomputer Fugaku provided by **RIKEN**.