

WG2 Summary – AAC 2022

WG2 conveners:

David Bruhwiler (RadiaSoft)



Alexey Arefiev (UCSD)



Advanced Accelerator Concepts (AAC) workshop

Hauppauge, New York
November 11, 2022

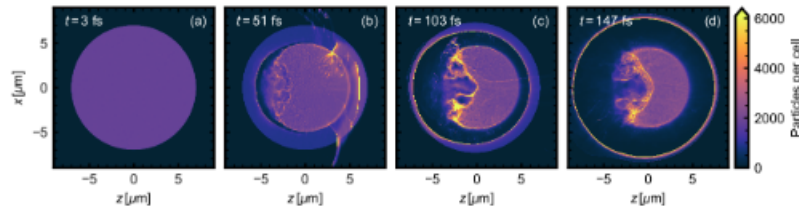
Outline

- Exascale PIC
 - WarpX
 - PIconGPU
- Integrated Infrastructure – Software and Facilities
 - virtual facilities / digital twins
 - integration with experimental facilities
 - synthetic diagnostics
 - machine learning
 - standards: code coupling, code integration, workflows, online models, ML
- Reduced models:
 - quasi-static & cylindrical PIC
 - MHD for plasma channel formation
 - beam loading in TW linacs
- PIC algorithms
 - ionization physics
 - current deposition
 - particle pusher
 - moving towards strong-field QED
- Other algorithms
 - Vlasov with mesh refinement
 - differentiable computing
 - high-power laser amplifiers
- Simulation of experiments

Exascale PIC

Selected Challenges for Exascale Modeling - Supercomputing

Exascale Needs Active Load Balancing and often adaptive resolution

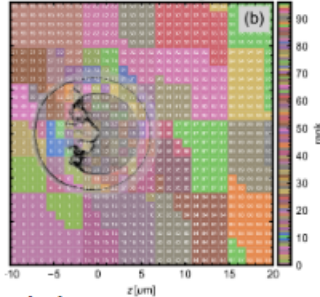


Density fluctuations:

beams & particles move

- LPI: acceleration front
- PBA: injected beam

Z-order space filling curve



Open challenges:

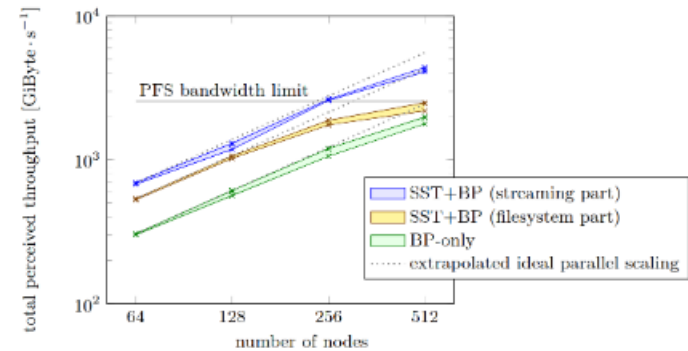
- communication cost model
- sub-step balancing

K Germaschewski et al., JCP ('16); J Derouillat et al., CPC ('18)
M Rowan et al., PASC21 ('21); K. G. Miller et al., CPC ('21)

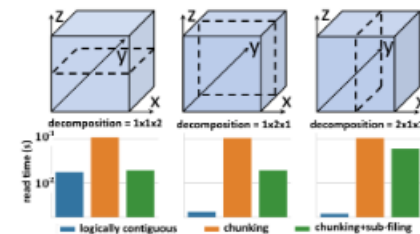
Concepts for PByte-Scale Data Analysis

main contributors: Axel Huebl, Franz Poeschel, Michael Bussmann, Norbert Podhorski, William Godoy, Lipeng Wang, Junmin Gu, Scott Klasky, et al.

Streaming Data Pipelines:



F Poeschel, A Huebl et al., SMC21 (2022)



Impact of decomposition schemes when reading

Online Data Layout Reorganization:

L Wan, A Huebl et al., TPDS (2021)

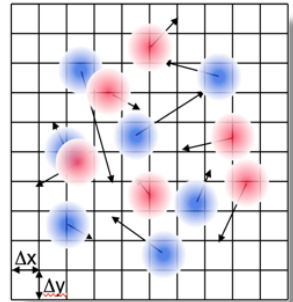
WarpX: Multi-Physics Particle-in-Cell Code for Exascale



Particle-in-Cell

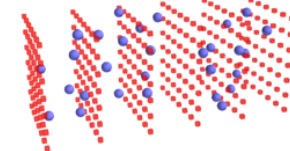
macro-particles

electro-magnetic (EM) fields on a grid

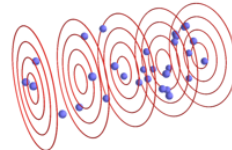


Geometries

- 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, Parallel I/O

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



Advanced Algorithms Pioneered by our Team

boosted frame, spectral solvers, Galilean frame, MR, ...

Multi-Physics Modules

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

Open source

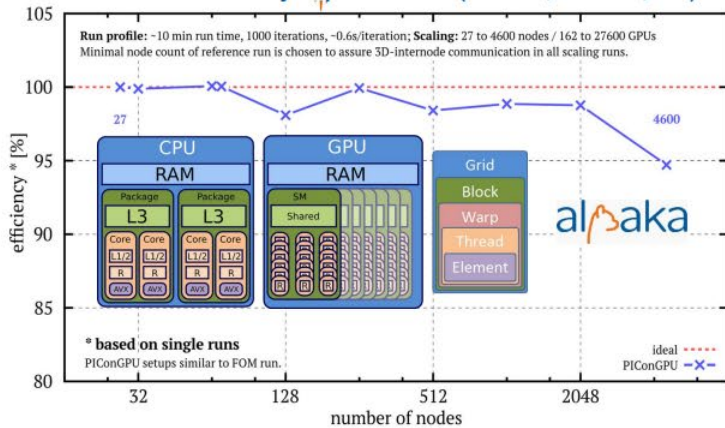


[ece-warpx.github.io](https://github.com/ece-warpx)

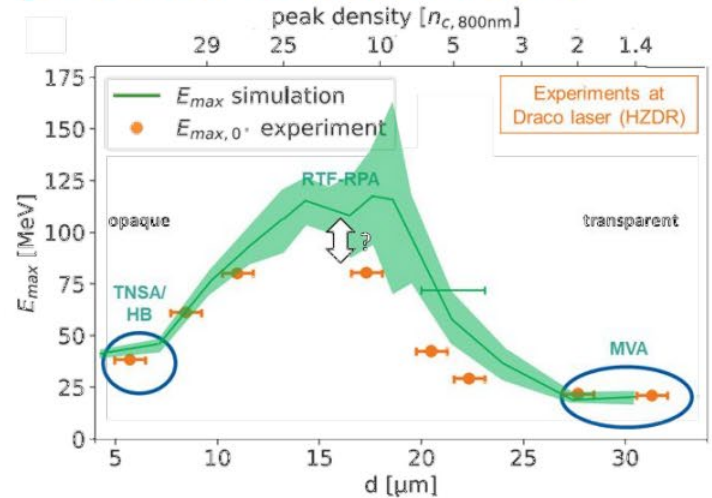
Michael Bussmann, Alexander Debus, Thomas Kluge, René Widera, Richard Pausch, Klaus Steiniger, Fin-Ole Carstens, Pawel Ordyna, Brian Marre, Ilja Göthel, Thomas Miethlinger, Anton Lebedev, Nico Hoffmann, Patrick Stiller, Anna Willmann, Franz Pöschel, Sergei Bastrakov, Bernhard Manfred Gruber, Jan Nikl, Marco Garten, Felix Meyer, Axel Huebl, Heiko Burau, Sunita Chandrasekaran, the experimental teams at HZDR, et al.!

PIConGPU: Exascale simulations for plasma accelerators

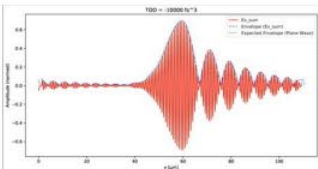
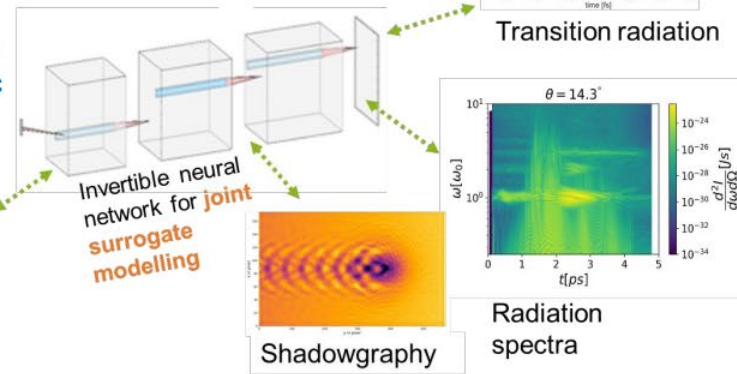
Excellent use of Exascale resources with Alpaka across all major platforms (CPUs, GPUs, ...)



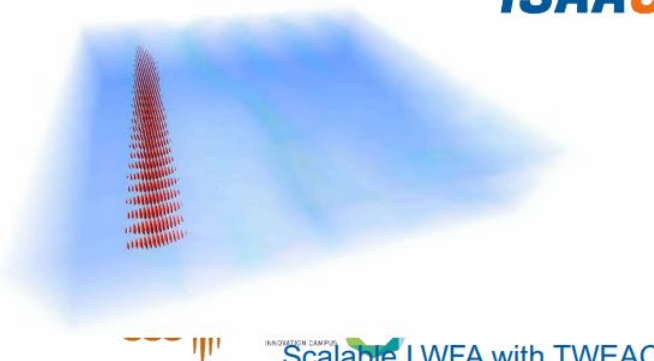
Predictive simulations of laser ion and LWF/PWF accelerators



Multi-modal surrogate modeling with synthetic diagnostics

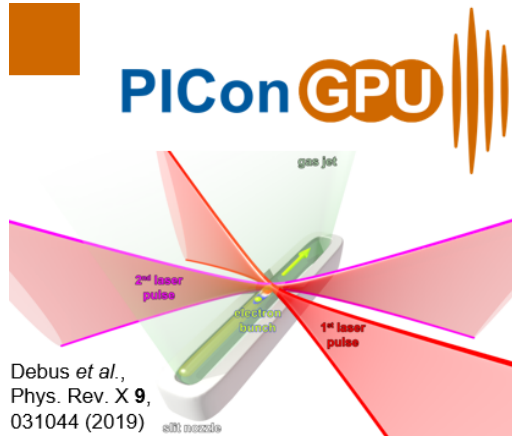


ISAAC



Exascale PIC

Alexander Debus¹, Klaus Steiniger¹, René Widera¹, Sergei Bastrakov¹, Finn-Ole Carstens¹, Felix Meyer¹, Richard Pausch¹, Marco Garten¹, Thomas Kluge¹, Jeffrey Kelling¹, Benjamin Hernandez Arreguin⁶, Jeffrey Young^{2,5}, Franz Pöschel², Axel Hübl⁴, David Rogers⁶, Guido Juckeland¹, Sunita Chandrasekaran^{2,3}, Michael Bussmann^{2,1}, Ulrich Schramm¹



Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

Traveling-wave electron accelerators Towards scalable laser-plasma accelerators beyond 10 GeV

Traveling-wave electron acceleration (TWEAC)

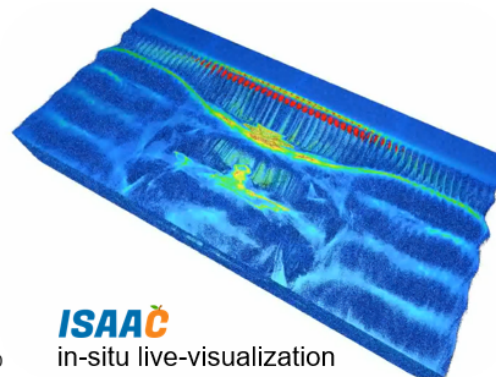
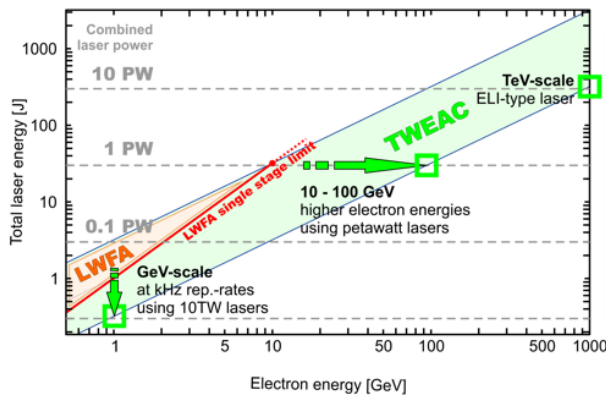
Simultaneously circumvents the LWFA limitations of diffraction, dephasing and depletion **without staging**.

Single-staged TWEAC are in principle arbitrarily extendable in length, providing new avenues for energy-scalable LPAs.

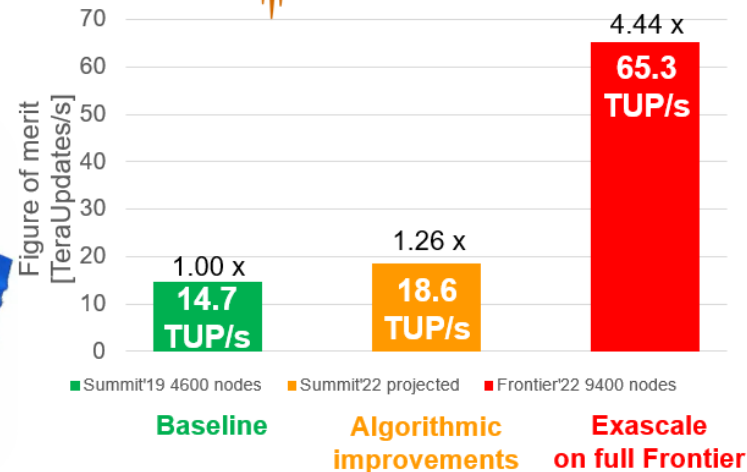


Simulating TWEAC beyond 10GeV at high-fidelity require exascale resources.

- Non-rotationally symmetric 3D geometry at high resolution.
- Long acceleration lengths far beyond LWFA depletion and dephasing need extended simulations over $10^6 - 10^7$ timesteps at reasonable time to solution.



PICon GPU scales to full Frontier!



Integrated Infrastructure – Software and Facilities

Snowmass21: Computational Frontier (CompF) report executive summary

Software and Computing (S&C) is essential to all experiments and many theoretical studies. The size and complexity of S&C is now commensurate with that of experimental instruments. Furthermore, S&C often specialization, and increased use of high-performance computing facilities. HEP is a significant user of national supercomputing computing centers through large and small experiment/survey workflows and corresponding simulations, theory (predominately lattice field theory), and accelerator modeling. Significant progress has also been made to prepare for future exascale computing resources.

The goal of Snowmass is to provide input for the Particle Physics Project Prioritization Panel (P5) with a ten year timescale. While clearly S&C is a science driver, it is not managed like a 'project' as in the case of facilities, experiments, and surveys. S&C is no less important, often transcends traditional boundaries, and changes on a much faster timescale than Snowmass processes. For this reason, we have identified one central recommendation for the 2021 Snowmass:

Integrated Infrastructure – workflows & standards

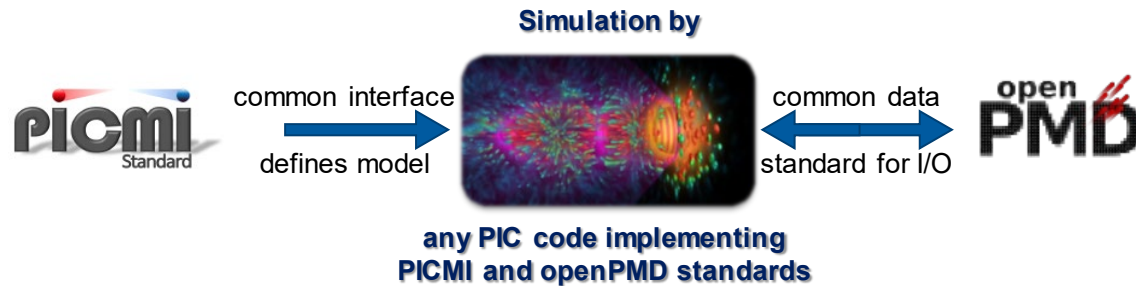
Now that we have Exascale, what can we do with it? PIConGPU for next generation Accelerator Research

Michael Bussmann, Alexander Debus, Thomas Kluge, René Widera, Richard Pausch, Klaus Steiniger, Fin-Ole Carstens, Pawel Ordyna, Brian Marre, Ilja Göthel, Thomas Miethlinger, Anton Lebedev, Nico Hoffmann, Patrick Stiller, Anna Willmann, Franz Pöschel, Sergei Bastrakov, Bernhard Manfred Gruber, Jan Nikl, Marco Garten, Felix Meyer, Axel Huebl, Heiko Burau, Sunita Chandrasekaran, the experimental teams at HZDR, et al.!

Standardization, testing and workflows

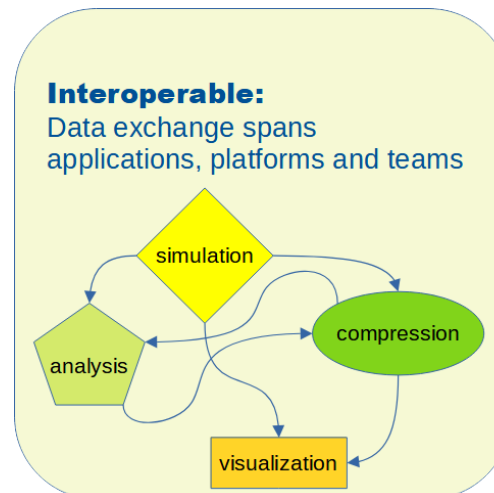
Challenges:

Standardization of
Code architectures,
implementation details
and physics capabilities



More data
Digital
Twins

Complex workflows, streaming data



Interoperable:

Data exchange spans
applications, platforms and teams

Reusable:

Rich and standardized description
for physical quantities

Name	Value
axisLabels	[b'z' b'y' b'x']
dataOrder	b'C'
fieldSmoothing	b'none'
geometry	b'cartesian'
gridGlobalOffset	[0. 0. 0.]
gridSpacing	[4.252342 1.0630856 4.252342]
gridUnitSI	4.1671151662e-08
position	[0. 0. 0.]
timeOffset	0.0
unitDimension	[-3. 0. 1. 1. 0. 0. 0.]
unitSI	15399437.98944343

Integrated Infrastructure – workflows & standards

Jean-Luc Vay

Lawrence Berkeley National Laboratory

On behalf of the WarpX team
LBNL, LLNL, SLAC, CEA, DESY, Modern Electron, CERN

Latest advances in the Particle-In-Cell
code WarpX for efficient modeling of
plasma accelerators at Exascale



Thoughts toward the establishment of a 10-year roadmap for advanced accelerator concepts computation

Proposal

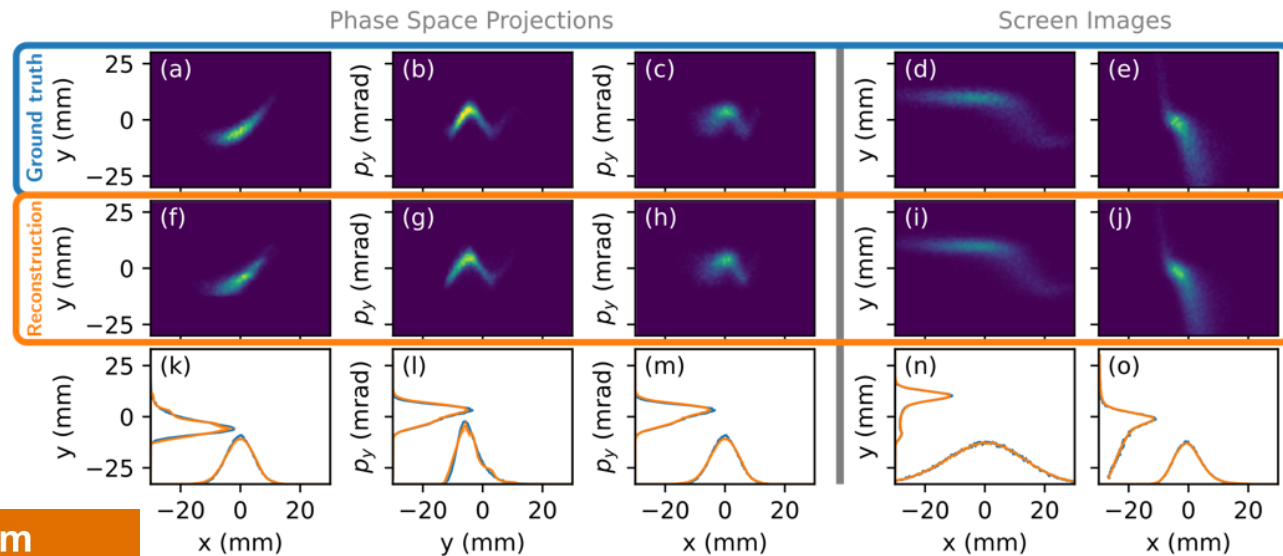
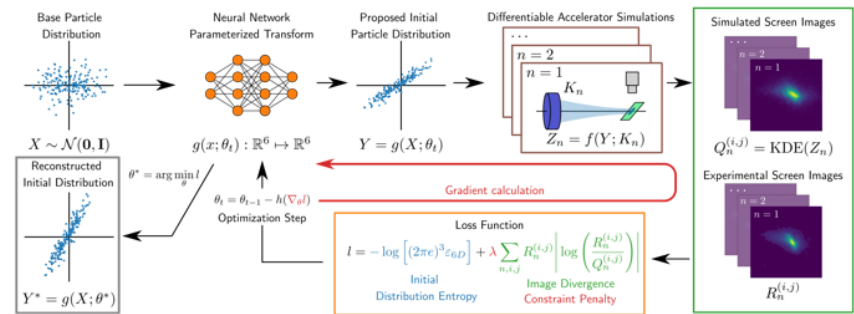
- Ultimate goal: End-to-end Virtual Accelerators (EVA) with on-the-fly tunability from users of physics & numerics complexity
- Development and adoption of input/output standards as early activities of roadmap
- Development of workflows with plug & play swap of models/codes enabled by standards
- Development of EVAs and Virtual Test Stands (VTS) for various AAC thrusts (LWFA, PWFA, SWFA, DLA, ...)
- Application of EVAs and Virtual Test Stands (VTS) for various AAC thrusts with milestones
 - E.g., for LWFA: model chain of 10 multi-GeV stages for HEP collider, maximizing beam charge and energy gain, and minimizing energy spread and emittance growth

Phase Space Reconstruction from Accelerator Beam Measurements Using Neural Networks and Differentiable Simulations



- We can create **detailed reconstructions of beam phase spaces** from simple tomographic accelerator measurements without special diagnostics

Details <https://arxiv.org/abs/2209.04505>



Phase Space Reconstruction from Accelerator Beam Measurements Using Neural Networks and Differentiable Simulations

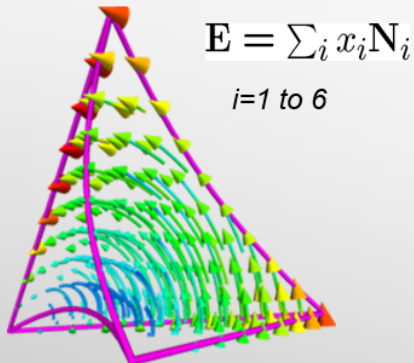
ACE3P – MULTIPHYSICS MODELING, ENABLING TECHNOLOGIES, AND CODE INTEGRATION

Liling Xiao

TID RFAR COMPUTATIONAL ELECTRODYNAMICS DEPARTMENT



- **ACE3P**, developed at SLAC, is a parallel multiphysics code suite including electromagnetic (EM), thermal and mechanical simulations for virtual prototyping of accelerator and rf components.
 - Based on *curved high-order finite elements* for high-fidelity modeling
 - Implemented on *massively parallel computers* for increased memory (problem size) and speed
 - Software infrastructure facilitates linking to third-party numerical libraries (with GPU capabilities)



Cori: Cray XC40

- 632,672 compute cores
- 1 petabytes of memory
- peak performance of 27.9 petaflops/sec

Perlmutter:

- 1536 GPU accelerated nodes
- 3072 CPU-only nodes
- peak performance: 3-4 times Cori

Libraries in linear algebra, linear solver, eigensolver, partitioning and data format:

- BLAS, LAPACK, ScalAPACK
- MUMPS, SuperLU, Trilinos
- PETSc
- ARPACK
- ParMetis
- Netcdf, HDF5

[Finite-element field representation](#)

[HPC at NERSC](#)

[Numerical libraries](#)

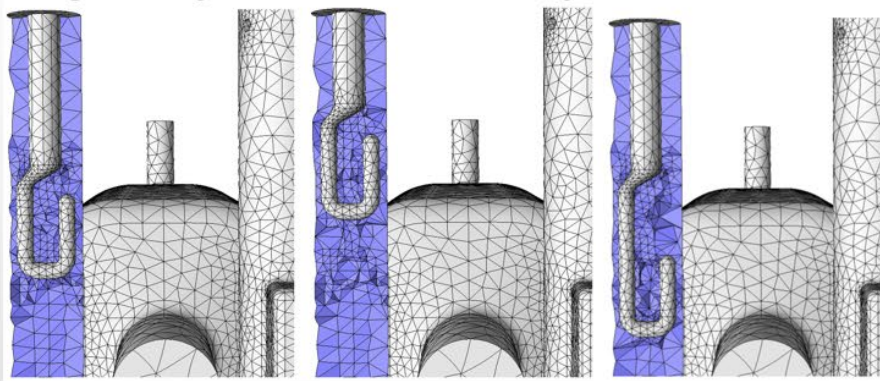
Aiming for virtual prototyping of rf components with fast turn around time.

Liling Xiao

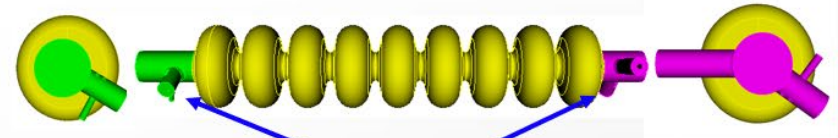
ENABLING TECHNOLOGIES FOR ACE3P SHAPE OPTIMIZATION



Automated Geometry and Mesh Updates for Accelerator Shape Optimization (Simmetrix, Inc.)
supported through SBIR (2019 to 2021)

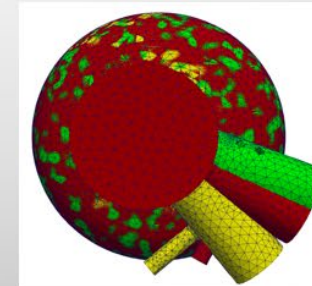


Optimization of LHC crab cavity input coupler



Design parameters at TESLA SRF cavity end-groups

- **Simmetrix**: Meshing tools for calculating design velocity ($\delta x / \delta d$ on boundary) and updating mesh after design parameter changes
- **SLAC**: Tool deployment into ACE3P's adjoint-based shape optimization code



Three iteration meshes with different HOM tank rotate and loop angles.

PIC algorithms

PIC algorithms: ionization physics

Efficient algorithms for multi-level ionization of high-atomic-number gases and applications

Speaker: Aiqi Cheng¹

Co-authors: Roman Samulyak¹, Rotem Kupfer², Navid Vafaei-Najafabadi¹

This algorithm is able to

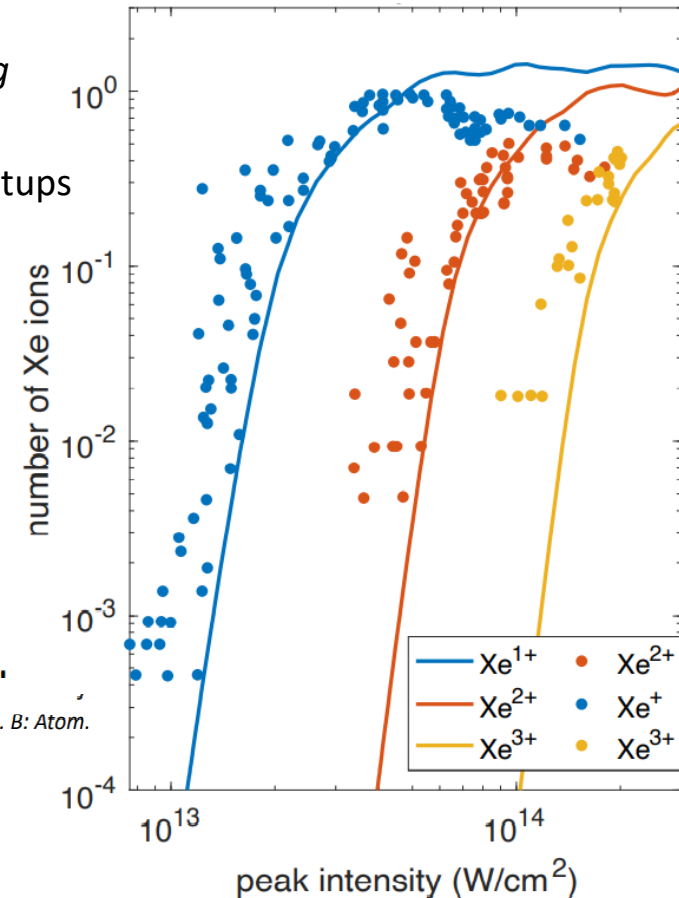
- **resolve time scale difference between the ionization process and PIC computation time step** by implementing analytical solution of the ionization dynamics
- **reduce the memory allocation** from recording number densities of different ion levels by solving 4-level ODE system, which **greatly improves the efficiency of computation**

Implementation into the 3D SPACE code enables some application including

- Computing ion yield from certain lasers from 3D
- Simulating ionization injection from high-Z gas in various experimental setups

Future plans:

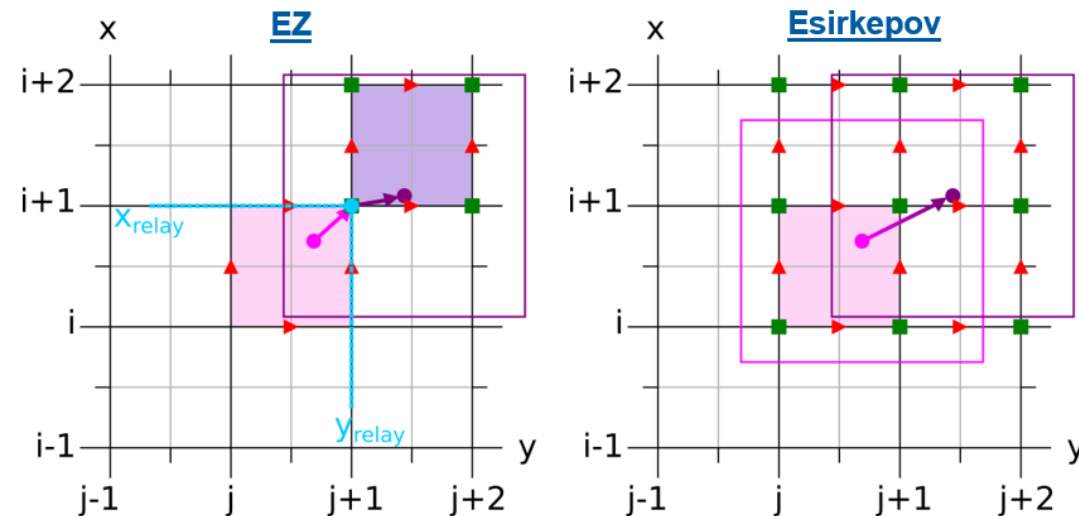
- reduced order models
- specialised MHD codes for long-time-scales
- novel methods for particle cooling
- integrated modeling and software



[3] F. Yergeau, S. L. Chin, and P. Lavigne, "Multiple ionisation of rare-gas atoms by an intense CO₂ laser ($10^{14}\text{W}/\text{cm}^2$)," *J. Phys. B: Atom. Mol. Phys.*, vol. 20, no. 4, pp. 723–739, Feb. 1987, doi: [10.1088/0022-3700/20/4/013](https://doi.org/10.1088/0022-3700/20/4/013).

EZ: An Efficient, Charge Conserving Current Deposition Algorithm for Electromagnetic Particle-In-Cell Simulations

EZ saves computations (red triangles) compared to Esirkepov's method by splitting the particle trajectory.



Consistent observation of percent-level speedup

On total time step in a warm, relativistic plasma.

E.g. for 2nd order assignment function TSC:

NVIDIA V100:	1.083 speedup
AMD MI100:	1.046 speedup
AMD EPYC CPU:	1.137 speedup

Speedup varies depending on assignment function order and compute architecture.

K. Steiniger, R. Widera, et. al.,

„EZ: An Efficient, Charge Conserving Current Deposition Algorithm for Electromagnetic Particle-In-Cell Simulations“, submitted to *Comp. Phys. Comm.*

Daniel Gordon, Bahman Hafizi, Dan Younis

Special Unitary Particle Pusher



By making use of the spinor representation of a four-vector, an exact time translation in an arbitrary uniform field can be compactly written

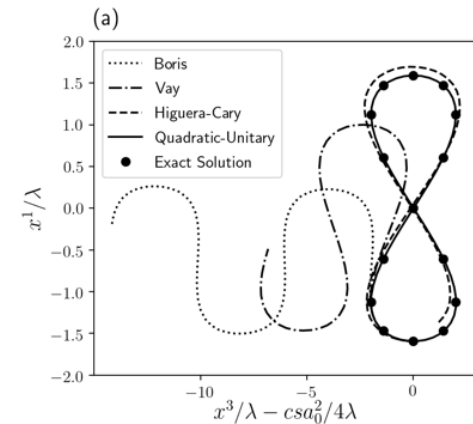
$$\zeta = \begin{pmatrix} u^0 + u^3 & u^1 - iu^2 \\ u^1 + iu^2 & u^0 - u^3 \end{pmatrix}$$

$$\zeta(s + \Delta s) = \Lambda(\Delta s)\zeta(s)\Lambda^\dagger(\Delta s)$$

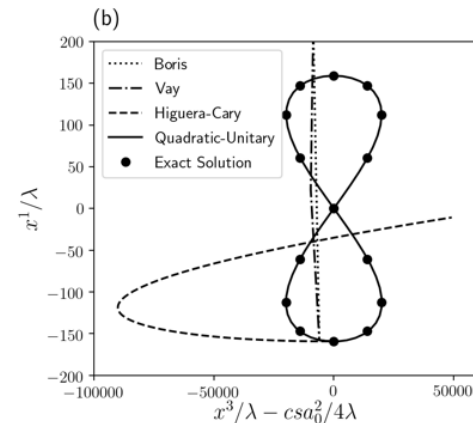
$$\Psi = \frac{\Delta s}{2} \frac{e}{mc} (\mathbf{E} + i\mathbf{B})$$

$$\Lambda(\Delta s) = \cosh \Psi + \boldsymbol{\sigma} \cdot \frac{\Psi}{\Psi} \sinh \Psi$$

$a=10$



$a=1000$



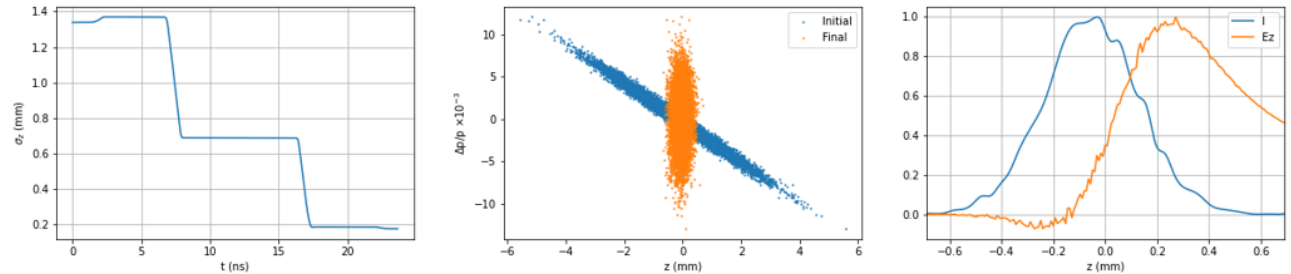
PIC algorithms: Lienard-Wiechert solver



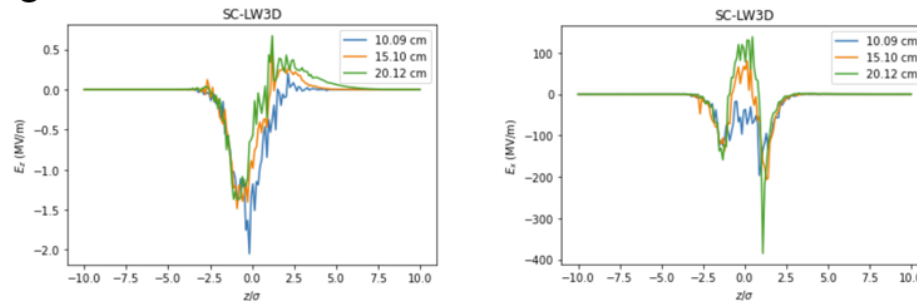
First-Principle Simulations of Electron-Bunch Compression Using a Large-Scale Lienard-Wiechert Solver, *Afnan Al Marzouk, Northern Illinois University*



- Used the LW3D first-principle large-scale code (developed by R. Ryne) to perform simulations to the bunch compressor at AWA and showed compression by a factor of 7.5 and computed CSR through the process.



- We are on the process of developing a self-consistent version of the LW3D to study the impact of CSR on the beam, which will also help investigate possible CSR mitigations.
- We showed initial results of the longitudinal and transverse wakefields that are different from the non-self-consistent results.



PIC algorithms: moving towards strong-field QED

Near-Field CTR beam focusing and its application to Strong Field QED

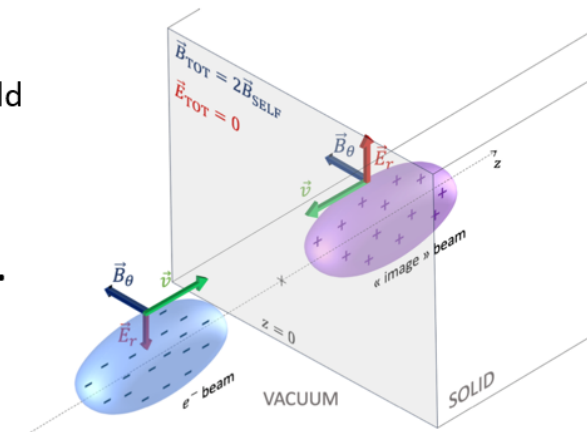
The intense EM fields produced at the surface of a solid conducting foil when interacting a high peak-current beam (**Near-Field CTR**) are interesting as:

- **Beam focusing elements to reach solid-density beams → bright gamma-ray source.**

Main motivation of E332 experiment at FACET-II:

- need high charge, low emittance and thin foils.
- Simulations show that substantial conversion efficiency should be measured with FACET-II nominal parameters

- **Laser-less scenario to probe the Strong-Field regime of QED.**
- Precision studies of SFQED.
- QED signal above competing processes.
- Intermediate step before beam-beam collisions.



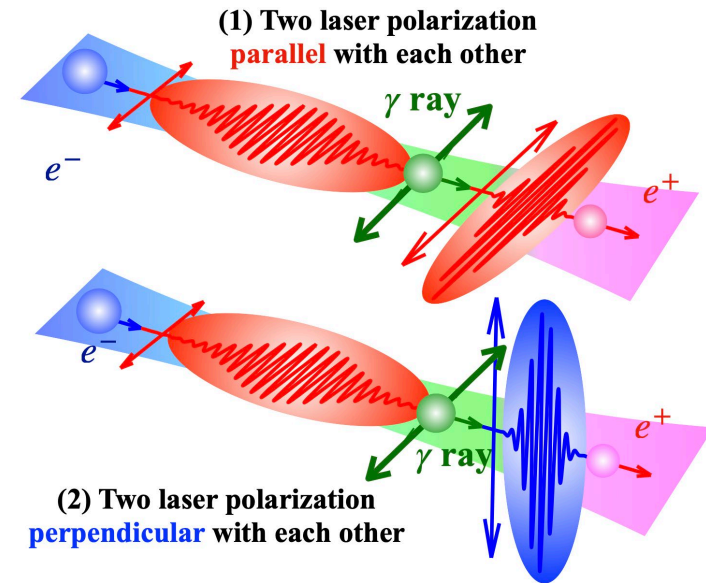
Pablo San Miguel



PIC algorithms: moving towards strong-field QED

Spin and polarization-dependent Osiris QED module for the future strong field QED laser-plasma experiment

Q. Qian,¹ D. Seipt,^{2,3} M. Vranic,⁴ T. Grismayer,⁴ T. Blackburn,⁵
C. P. Ridgers,⁶ A.G.R. Thomas¹

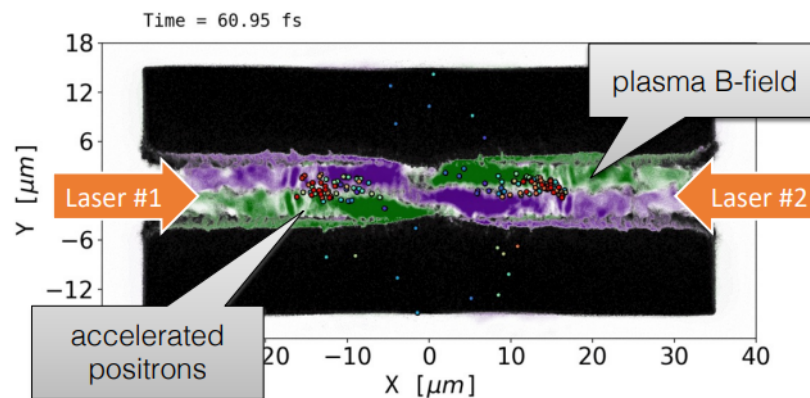


- Including the lepton spin and photon polarization in the QED calculation of the PIC code is necessary. They strongly influence the NLC and NBW spectrum.
- Spin and polarization-resolved quantum radiation reaction module is now developed based on PIC code Osiris. The code passed the benchmark tests and could reproduce the published results.
- A two-pulses involved pair-production scheme is proposed. This scheme offers a controlled way to study how the photon polarization state will influence the NBW process and also provide proof for the spin and polarization-resolved NBW theory.

PIC algorithms: positron production

A. Arefiev (UCSD)

- ▶ Two-photon pair production inside a laser-irradiated plasma can be efficient even at currently available laser intensities.
- ▶ The plasma provides acceleration mechanisms that generate collimated beams of ultra-relativistic positrons.
- ▶ Positrons can be produced and accelerated using a single laser or two counter-propagating lasers.



Reduced Models

Reduced models: quasistatic PIC

Qianqian Su¹, Fei Li¹, Weiming An², Yujian Zhao¹, Lance Hildebrand¹,
Viktor Decyk¹, Paulo Alves¹, Ann Almgren³, Warren Mori¹

¹ University of California, Los Angeles, US

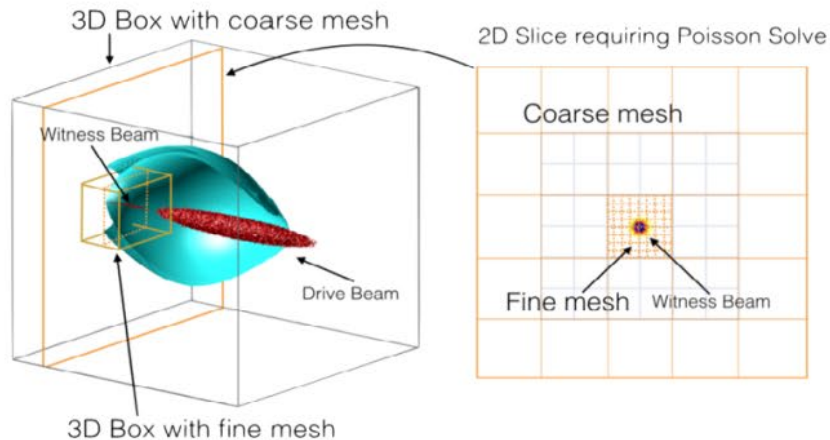
² Beijing Normal University, Beijing, China

³ Lawrence Berkeley National Lab

UCLA

Electrical & Computer Engineering Department

Mesh refinement in QuickPIC



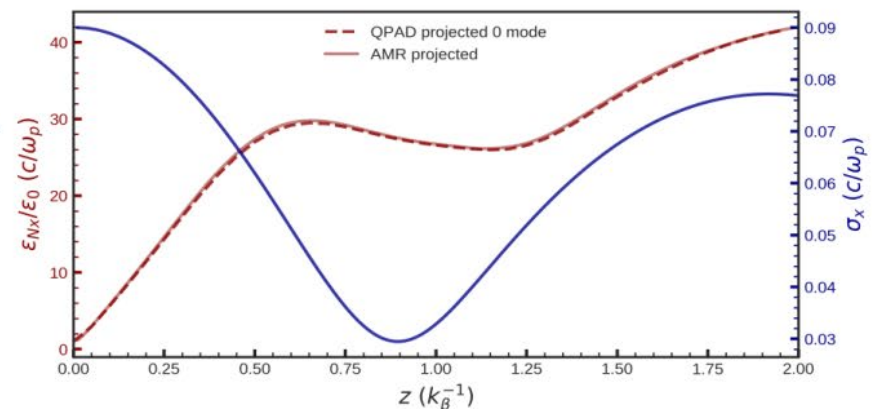
We also developed an adaptive mesh refinement option for an evolving beam and enables significant speed up.

Several benchmark cases have been tested and get consistent result as previously published papers and a Quasi-3d QS PIC code QPAD.

We have developed a MPI + OpenMP parallelized mesh refinement code based on QuickPIC

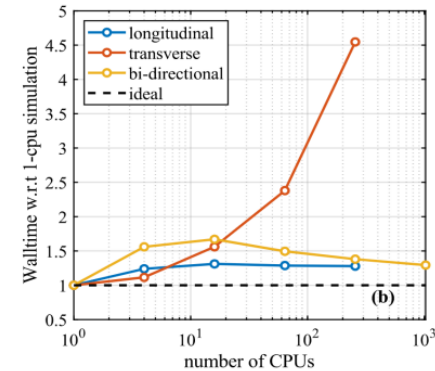
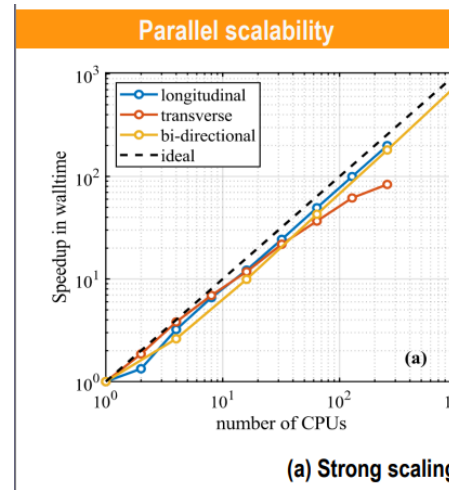
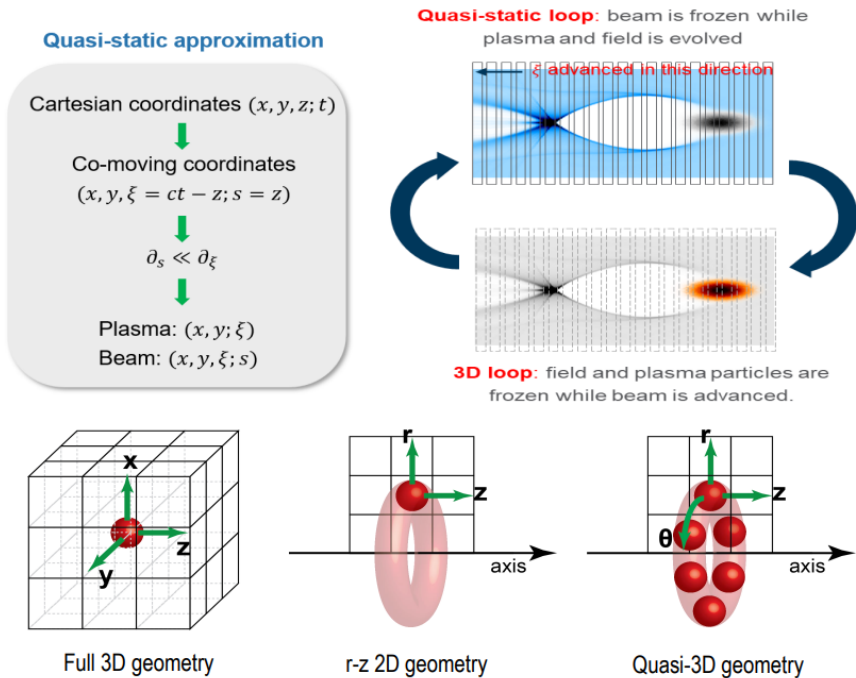
Estimation of roughly a thousand times speed-up compared to full QuickPIC with fine resolution everywhere

The scalability of the code has been improved by using pipelining and improving load balancing.



QPAD: Highly Efficient Quasi-static Particle-in-cell Algorithm Based on Azimuthal Decomposition

Fei Li, Weiming An, Qianqian Su, Thamine Dalichaouch, Frank Tsung and Warren Mori



- Computational complexity is much reduced and is comparable to 2D r-z geometry.
- Azimuthal decomposition can speed up QSA simulations by **~2 orders of magnitude**.
- Compared with full 3D PIC simulations, QPAD can reduce the computational complexity by **5-7 orders of magnitude**.

Li, F., et al. *Computer Physics Communications*, 261, 107784 (2021).

Li, F., et al. *Journal of Computational Physics*, 470, 111599 (2022).

Reduced models: quasistatic PIC

HiPACE++: a portable, 3D quasi-static Particle-in-Cell code

S. Diederichs,^{1,2,3} C. Benedetti,² A. Huebl,² R. Lehe,²
A. Myers,² A. Sinn,¹ J.-L. Vay,² W. Zhang,² and M. Thévenet¹

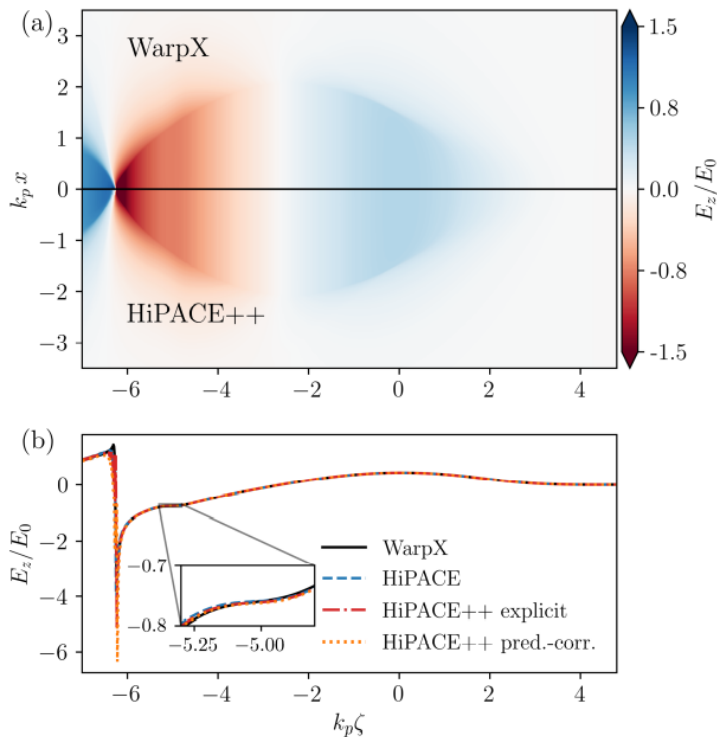
¹Deutsches Elektronen-Synchrotron DESY, Germany

²Lawrence Berkeley National Laboratory, USA

³University of Hamburg, Germany

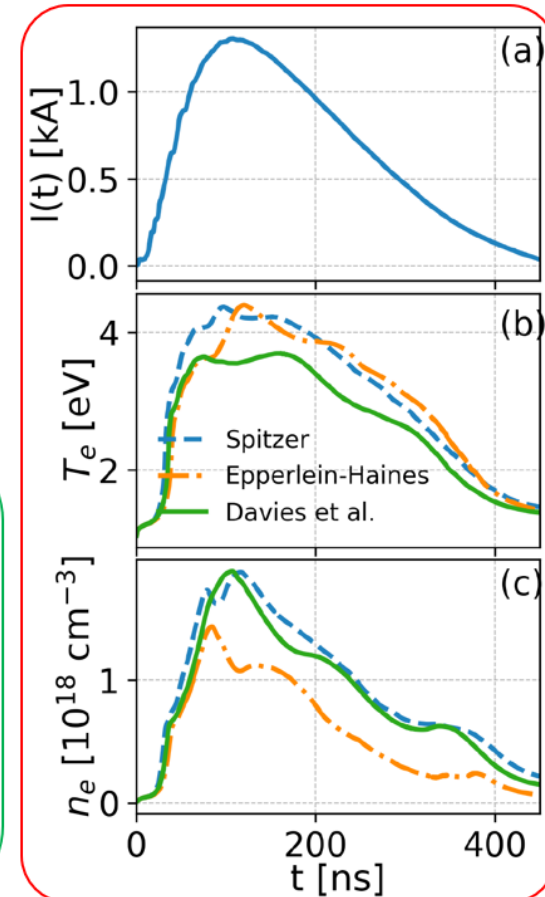
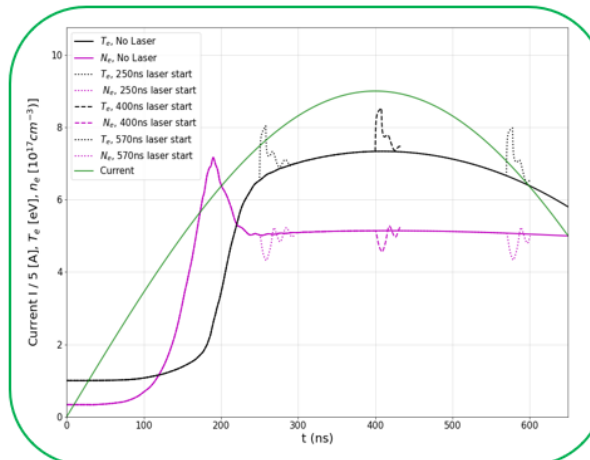
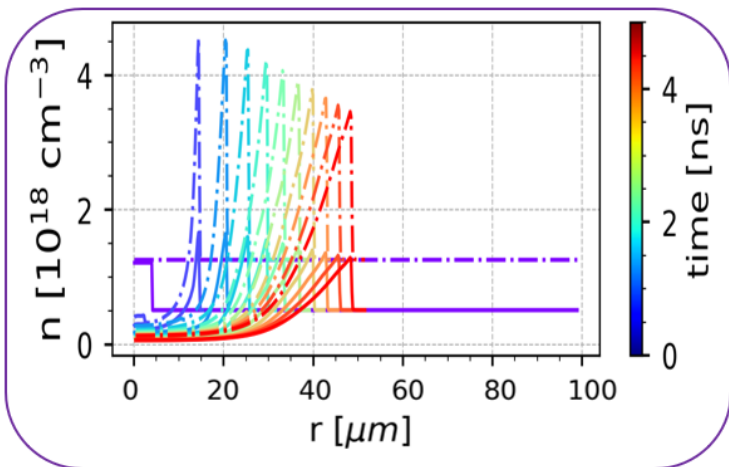
Single GPU easily outperforms many CPU cores

Benchmark and performance



FLASH simulations enable MHD study of structured plasmas

- Developed 2D and 3D simulations of a variety of AAC plasma systems
 - Capillary discharge plasmas for active plasma lens applications
 - Laser-heated capillary discharges for high intensity laser waveguides
 - Hydrodynamic optically-field-ionized plasmas for meter-scale channels
- Specific efforts explore impact of underlying models and assumptions
 - Anisotropic transport models reduce steady state temperature and density
 - Equation-of-state and opacities influence early time-scales of channel formation
- Simulation tools are accessible through publicly-available [Sirepo.com](https://sirepo.com) portal



Reduced models: MHD simulation of plasma channel formation

Simulations of Hydrodynamic Optical-Field-Ionised Plasma Channels

🕒 15m



Recent results have demonstrated hydrodynamic optical-field-ionised plasma channels as being a promising plasma source for efficient, high-repetition-rate laser plasma accelerators.

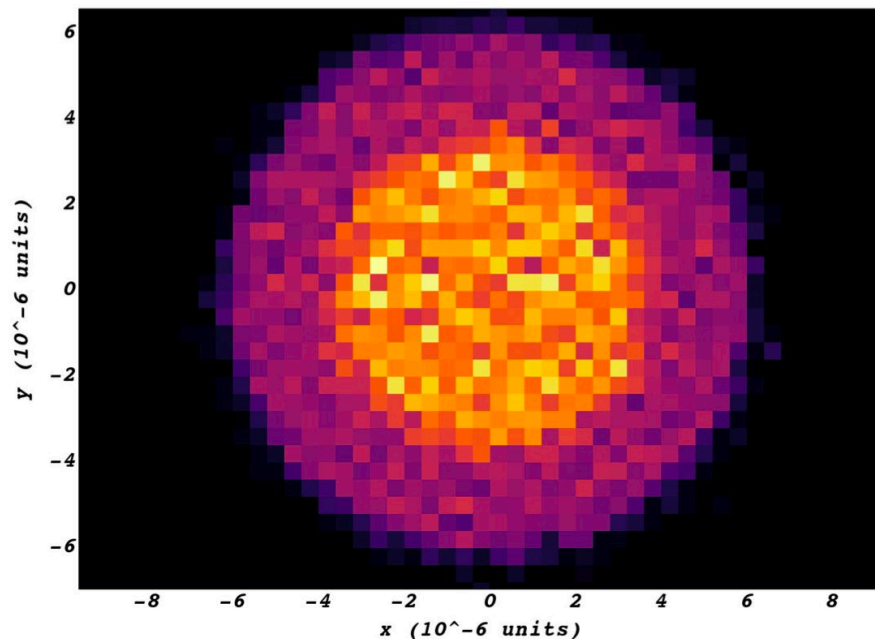
Understanding the dynamics of these plasma waveguides is critical to improving their performance and for tailoring their modal properties to fit a given experimental setup. This can be challenging as the important physical processes span multiple orders of magnitude with ionisation/heating on femtosecond timescales, thermalisation on picosecond timescales, and expansion/waveguide formation on nanosecond timescales.

Here, we present simulation results capturing the key dynamics of these plasma structures from ionisation to waveguide formation and benchmark the results against experimental data. Further, we explore how key experimental parameters can be used to tune the waveguides properties.

Speaker: Dr Rob Shalloo (DESY)

GPU Accelerated Simulations of Channel Formation for LWFA

Jarrold Leddy¹, Steven Lanham¹, Scott Sides¹,
Kathryn Wolfinger², Ilya Zilberter¹, John Cary^{1,2}



Reduced models: beam loading in TW electron linacs

Simulating electron beams in RF cavities with beam loading

David Bruhwiler,* Ilya Pogorelov,
Garret Sugarbaker and Robert Nagler

Sergey Kutsaev

Yury Eidelman

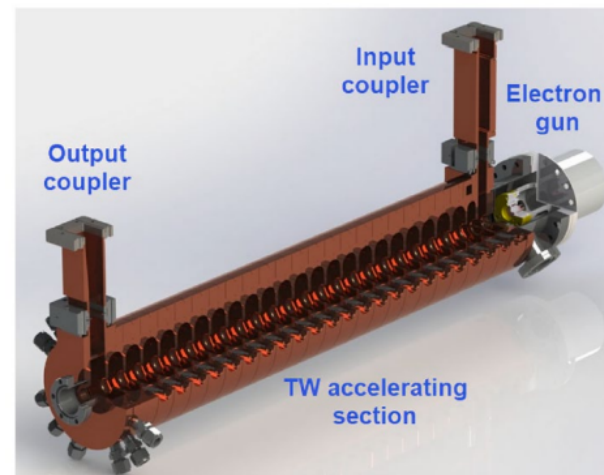
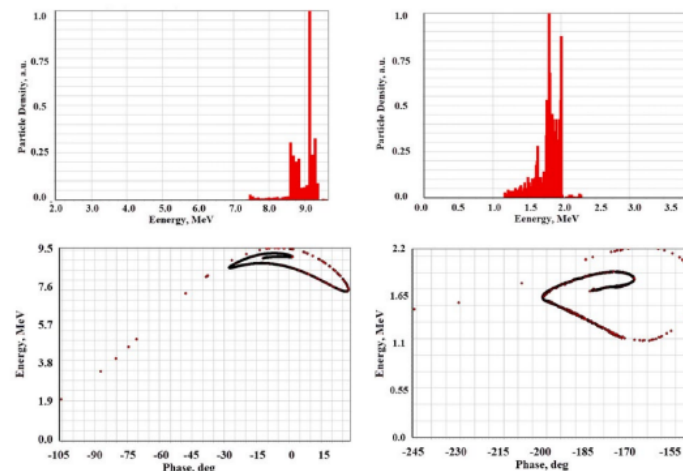


Fig. 3. Engineering design of a TW disk-loaded waveguide for the FLEX linac.

- Hellweg is a powerful reduced-model code for linac design
 - in production use for TW linacs that are being built and used
 - beam loading is automatically included
 - 1000x faster than CST, with quantitative agreement
- We are porting Hellweg to the AMReX framework
 - will enable GPU execution with orders of magnitude speedup
- Adding features, required for very high phase space densities
 - Touschek scattering
 - exploring symplectic algorithms



Other algorithms

Other algorithms: Vlasov with mesh refinement

Eulerian Finite-Difference Vlasov Solver with a Non-Uniform Momentum Grid

Prof. B. A. Shadwick (Univ of Nebraska - Lincoln)

Vlasov–Maxwell Equation

1-1/2 D

- ▶ Transformation between the logical and physical momentum:

$$p_x = P_x(\xi) \quad \text{and} \quad p_z = P_z(\eta)$$

- ▶ Transform the Vlasov–Maxwell equation:

$$f(z, p_x = P_x(\xi), p_z = P_z(\eta), t) = F(z, \xi, \eta, t)$$

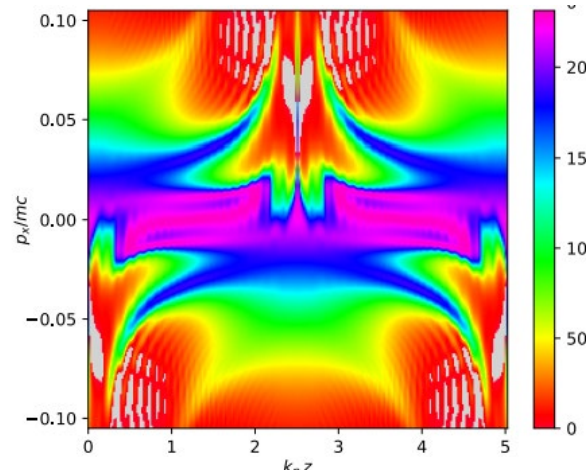
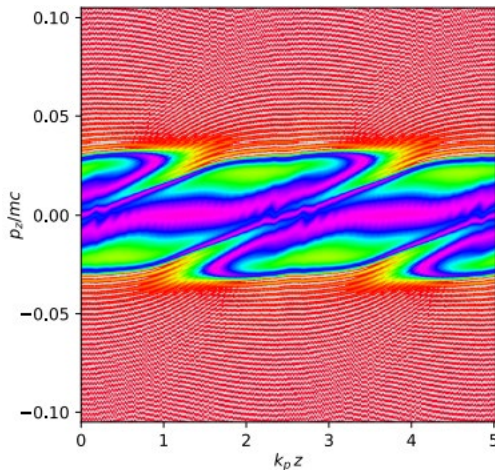
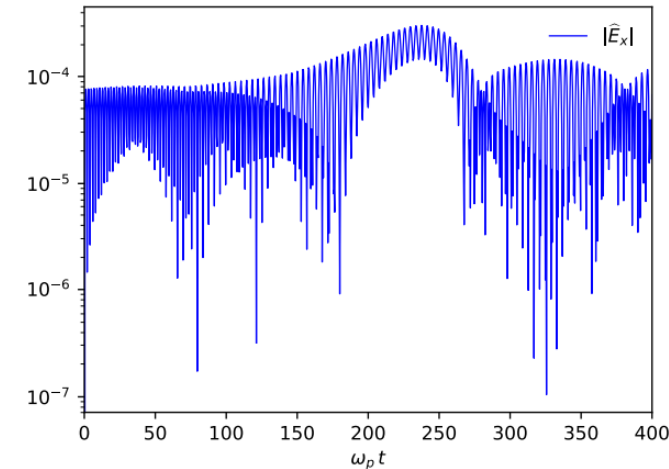
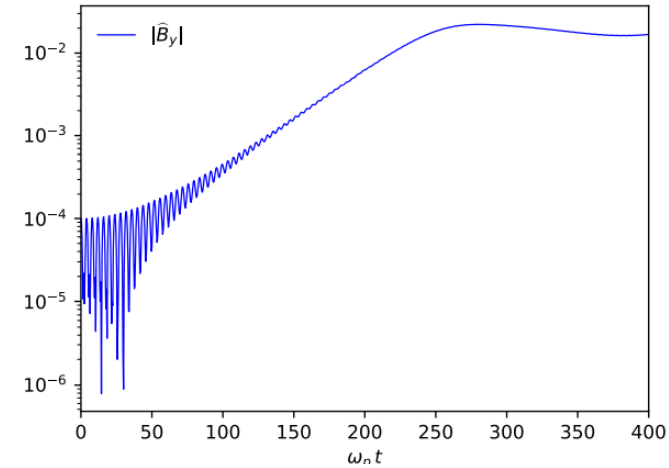
where

$$\frac{\partial F}{\partial t} + P_z(\eta) \frac{\partial F}{\partial z} + q \frac{E_x - P_z(\eta) B_y}{P'_x(\xi)} \frac{\partial F}{\partial \xi} + q \frac{E_z + P_x(\xi) B_y}{P'_z(\eta)} \frac{\partial F}{\partial \eta} = 0$$

and

$$J_x = q \int d\xi d\eta P'_x(\xi) P'_z(\eta) P_x(\xi) F$$

$$J_z = q \int d\xi d\eta P'_x(\xi) P'_z(\eta) P_z(\eta) F$$



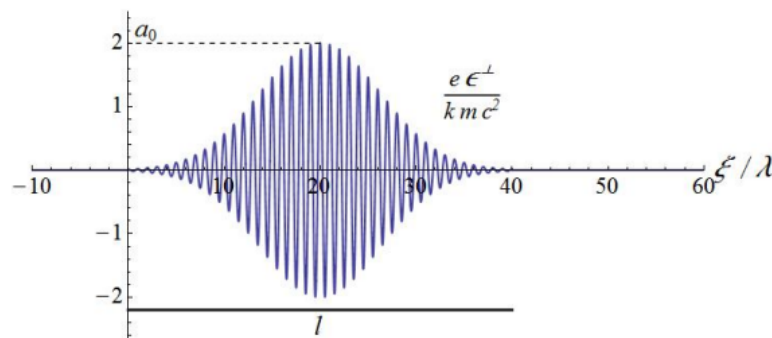
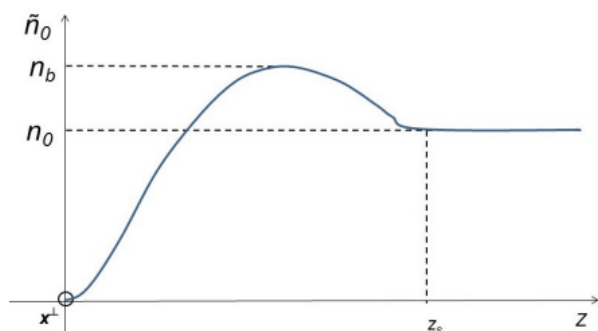
Other algorithms: 1D semi-analytic approach with wavebreaking

A preliminary analysis for efficient LWFA

Gaetano Fiore,
Università di Napoli, & INFN, Napoli
gaetano.fiore@na.infn.it



We propose an analytical procedure in 4 steps (based on an improved fully relativistic plane hydrodynamic model) to tailor the initial plasma density $\tilde{n}_0(z)$ and the laser pulse profile (see figure) so as to control the wave-breaking (WB) of the plasma wave and to maximize the acceleration of small bunches of self-injected e^- ; 1. finding the optimal value n_0^M of the plateau density n_0 ; 2. finding the optimal electron layers pairs to produce the first WB near $z = z_s$; 3. finding the corresponding optimal left slopes for \tilde{n}_0 near $z = z_s$; 4. adjusting $\tilde{n}_0(z)$ for $z < z_s$ to avoid earlier WB elsewhere.



Other algorithms: differentiable computing

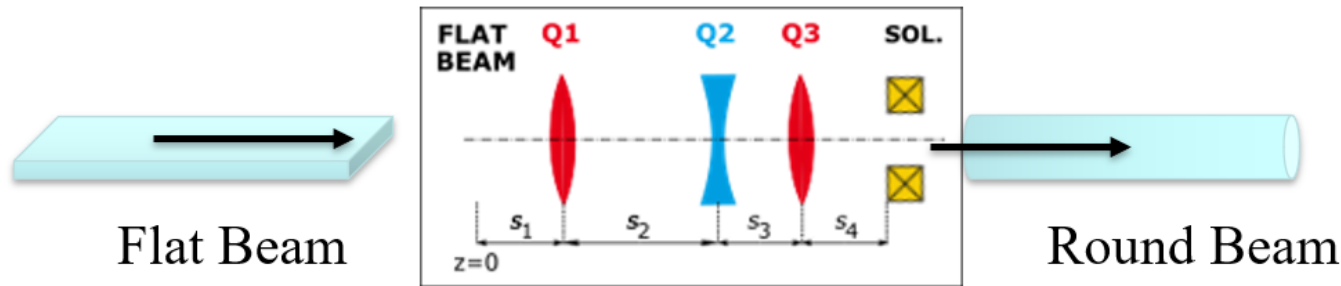
ADJOINT OPTIMIZATION OF CIRCULAR LATTICES

UMD Team

Efficient calculation of $\frac{dF(\mathbf{a})}{d\mathbf{a}}$

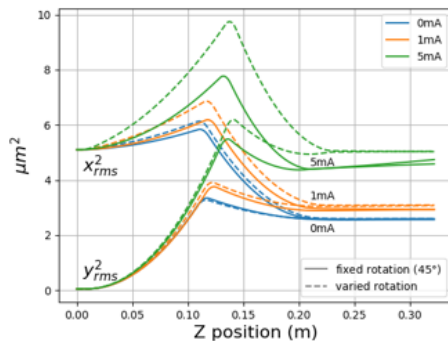
Where F is a Figure of Merit and where \mathbf{a} is a vector of parameters

N – Dimensional gradient calculated with one additional pass through lattice.



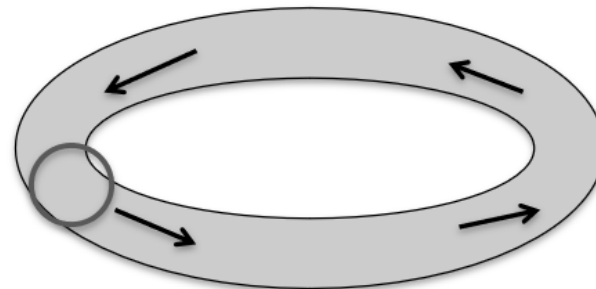
Optimization of Flat to Round Transformers Using Adjoint Techniques*

L. Dovlatyan, et al., Phys Rev Accel and Beams V25, 044002 (2022).



Optimization with strong self fields

Next up circular lattices



Other algorithms: High-power, high-rep-rate lasers

Thermal Modeling and Benchmarking of Crystalline Laser Amplifiers

At high power/intensity, thermal gradients can induce thermal lensing, astigmatism, and thermal bulging, as well as modify the birefringence.

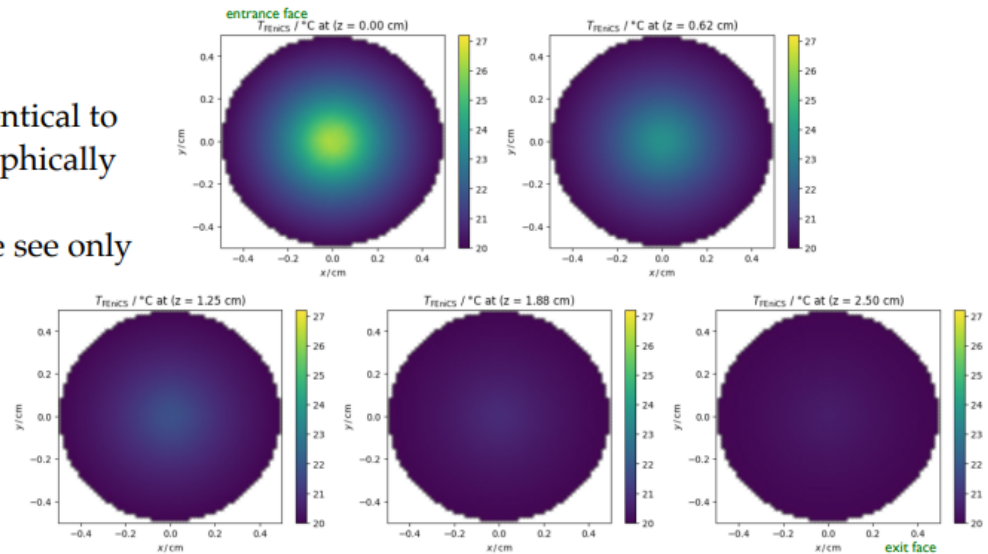
$$\text{Nonlinear heat equation: } \dot{u} = \nabla \cdot \left(\underbrace{\frac{\kappa(\theta)}{\rho(\theta)c_p(\theta)}}_{\alpha(\theta) \rightarrow \alpha(u)} \nabla u \right) + \frac{\kappa}{(\rho c_p)^2} \frac{\partial \rho}{\partial \theta} |\nabla u|^2 + \frac{1}{\rho} \dot{\epsilon}(\vec{r}, t)$$

Use specific heat capacity $c_p = \partial u / \partial \theta$ to connect u to θ .

- Near room temperature, these results appear nearly identical to those of the linear case. (Temperature lineouts appear graphically identical.)
- At an $\times 5$ power level—but still room temperature—we see only mild difference between the linear and nonlinear cases.

Lessons Learned: Obtain thermal data characteristic of *your crystal*.

Next Steps: Explore cryogenic temperatures, anisotropic heat conduction, and thermal expansion.



This work is supported by the US Department of Energy, Office of Science, Office of High Energy Physics under Award Numbers DE-SC0020931 and DE-AC02-05CH11231.

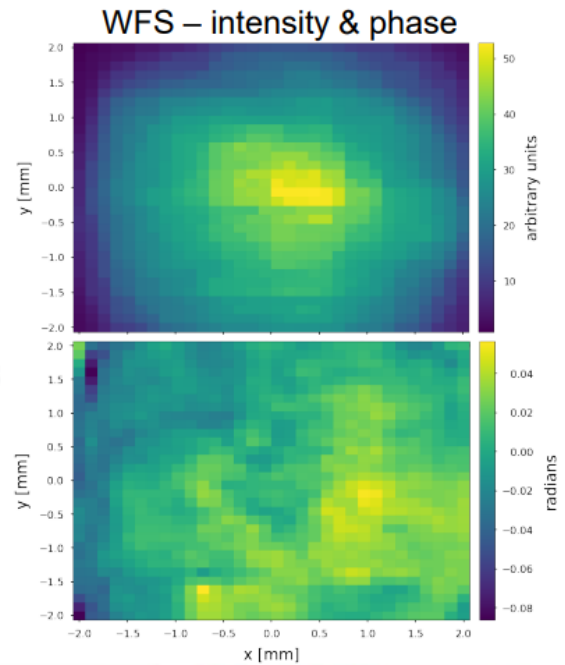
Other algorithms: High-power, high-rep-rate lasers

Simulation of electromagnetic pulses through high-power solid state laser amplifiers

David L. Bruhwiler,* Boaz Nash, Dan T. Abell,
Gurhar Khalsa and Robert Nagler (RadiaSoft)

Jeroen van Tilborg, Qiang Chen, Csaba Tóth,
and Cameron G.R. Geddes (LBNL)

Nicholas B. Goldring (STATE33 Inc.)

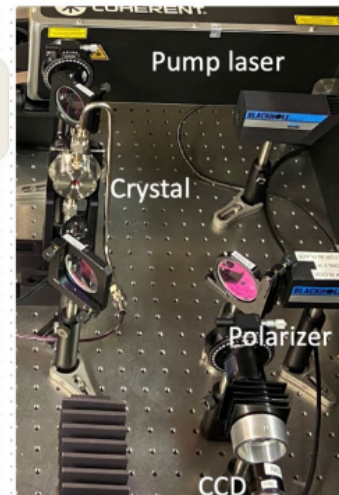
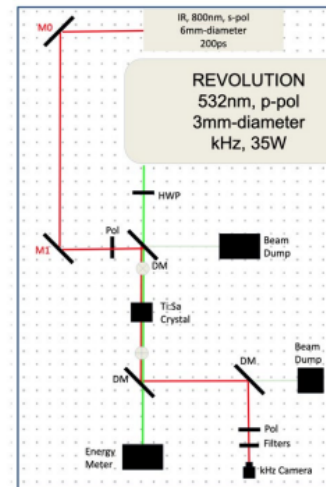


- PW lasers are moving toward KHz rep rates

- software is needed for crystal amplifiers
- Python library, <https://github.com/radiasoft/rslaser/>
- [Sirepo.com](https://sirepo.com) UI is being developed to support these capabilities

- Experiments at the BELLA Center enable validation

- experimentally observed thermal focusing at 1 KHz is stronger than expected
- possible explanations are being explored

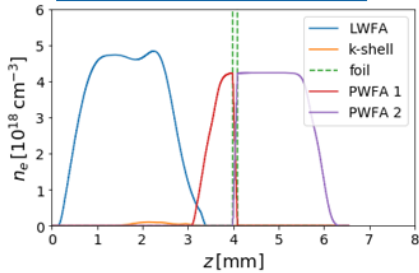


Simulation of experiments

Accurate modelling of experiment setups opens up predictive capabilities of simulations



Gas profile modelling

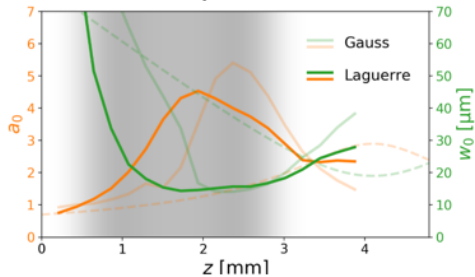


With modelling of **gas** and **laser** according to experiment measurements:

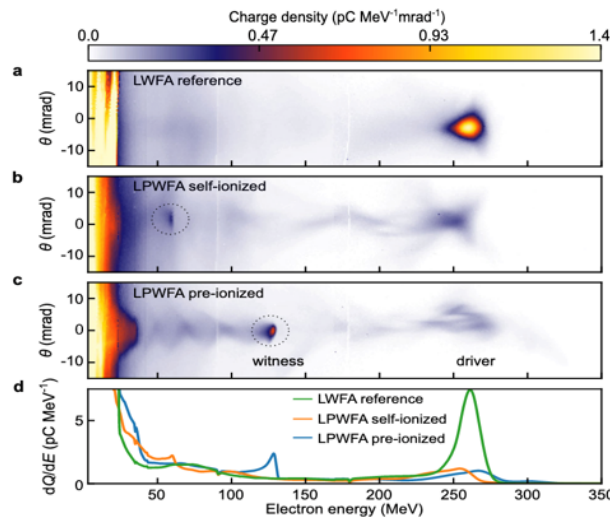
- Driver energy and energy spread close to experiment
- Driver degradation and witness acceleration as observed in experiment
- Witness peak energy in agreement with experiment

Laser modelling

- Energy
- transverse modes
- focal position



Experiment



Simulation

