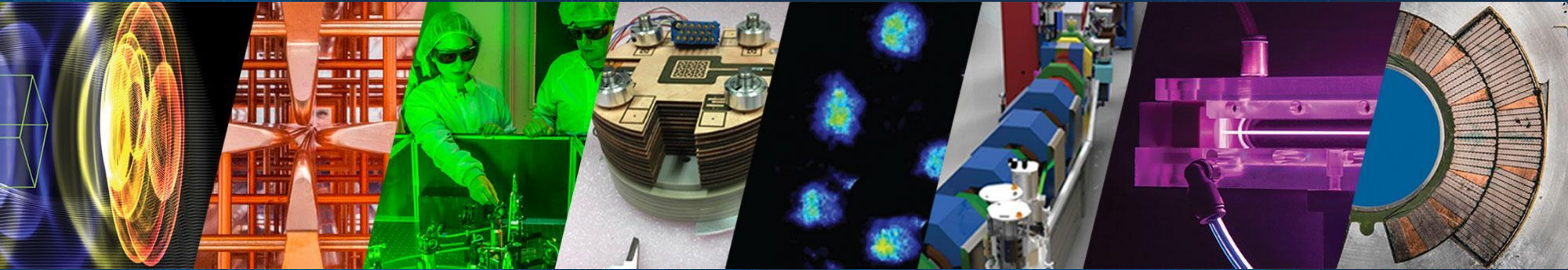
Boosting Laser-Driven Proton Beams to Relativistic Energies with Hollow-Channel Magnetic Vortex Acceleration and Readily Available Petawatt Laser Pulse Energy

***Marco Garten**, Stepan Bulanov, Sahel Hakimi, Lieselotte Obst-Huebl, Chad Mitchell, Carl Schroeder, Eric Esarey, Cameron G. R. Geddes, Jean-Luc Vay, and Axel Huebl*

Accelerator Technology & Applied Physics Division, Lawrence Berkeley National Laboratory, USA

arXiv:2308.04745 (2023)



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6th European Advanced Accelerator Concepts Workshop 2023 (EAAC'23)

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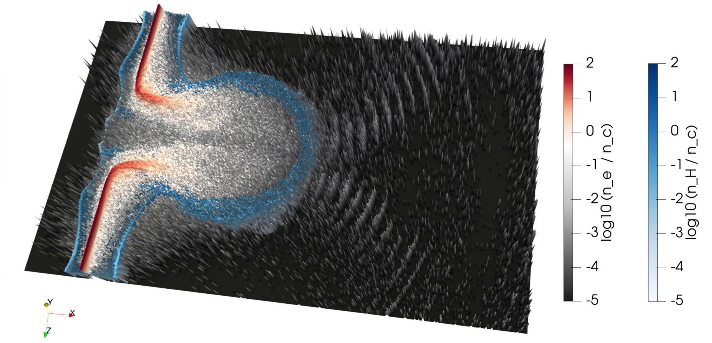
LPI Sources Provide Ion Bunches with Unique Characteristics that are Promising for Applications

- Laser-Plasma Ion (LPI) sources create ion bunches with:
  - Ultra-short duration $\lesssim$ 30 fs
  - Very high charge $\gg$ 100 pC
  - Ultra-low emittance and high laminarity, $\lesssim$ 10 nm·rad [1] (100x better than typical RF accelerators)
- Attractive for applications such as:
  - Radiation oncology
  - Inertial fusion
  - Materials science
  - Radiography & Imaging



ParaView visualization of a 3D WarpX simulation: BELLA iP2 laser interacting with 50nm LCT foil target

[1] Cowan et al., (2004). *Physical Review Letters*, *92*(20), 204801

Decoupling LPI Source from Energy Booster Can Remove Roadblocks towards Higher Energies

- Current records **60-100 MeV** [1-3] (~150 MeV DRACO,HZDR [4])

  ⇒ Falls just short of energies for, e.g., **radiation oncology**

- Despite extensive research, experiments of LPI sources are far from **relativistic energies**
- Due to their higher mass, ions require **quasi-static / co-moving fields** for much longer times than electrons
- **Field-inducing electrons** are either gone too quickly, or tailoring of co-moving fields is extremely tricky

  ⇒ Plasma-based proton wakefield accelerator concepts require **relativistic β** for injection and further acceleration

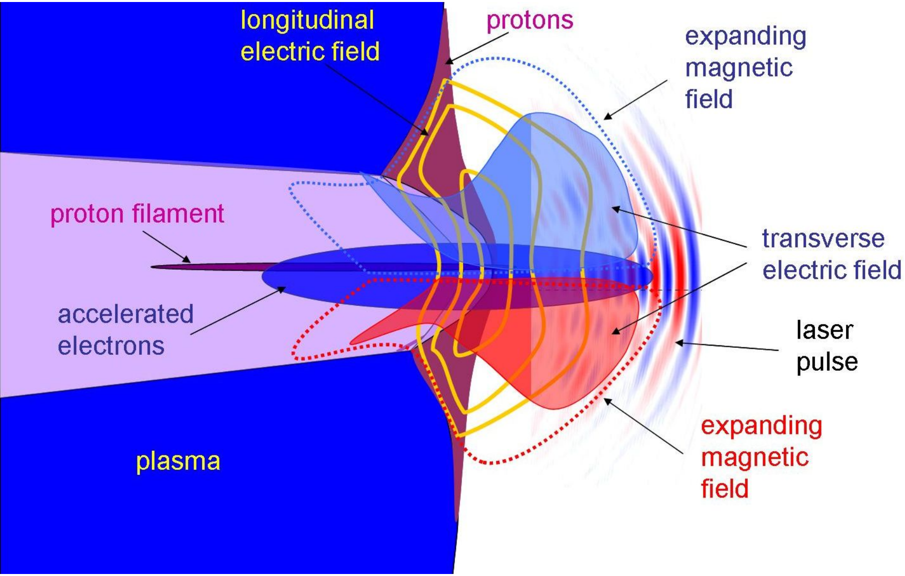
$\beta = v/c$

[1] F. Wagner, et al. (2016). PRL, 116, 205002
[2] Ziegler, T., et al. (2021). *SciRep*, *11*(1), 7338.
[3] Higginson, A., et al. (2018). *NatComm*, *9*(1), 724.
[4] Plenary by J. Metzkes-Ng on Thursday

Staged approach could be a solution

Magnetic Vortex Acceleration in Near-Critical Density (NCD) Plasma

Promising choice for source stage: MVA



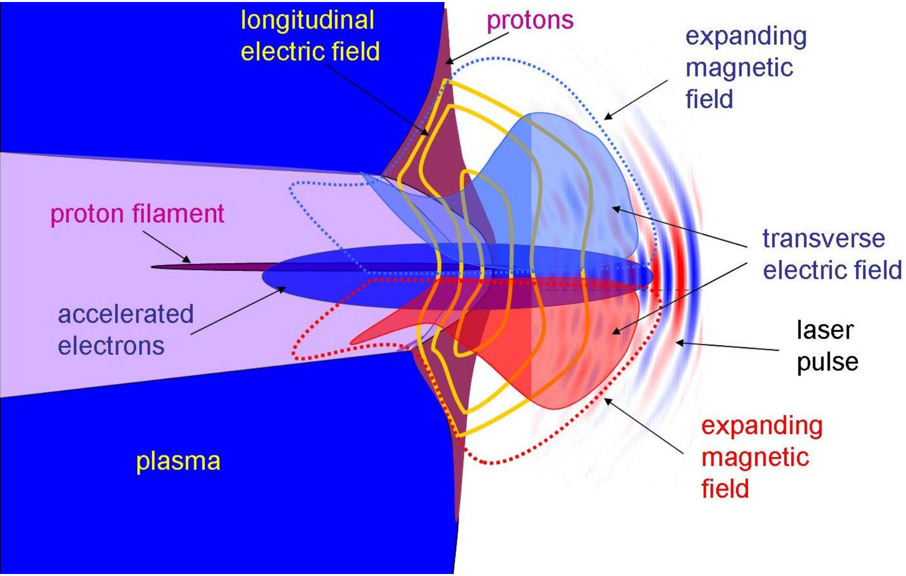
J. Park, *et al.*, Phys. Plasmas 26, 103108 (2019)
S. Hakimi *et al.*, Phys. Plasmas 29, 083102 (2022)

Reviewing the mechanism

- Intense laser pulse interacts with optically opaque, near-critical target
- Ponderomotive force generates plasma channel
- Strong electron current in forward direction which becomes pinched
- Interplay with return currents inside channel walls generates azimuthal magnetic field structure
- Expanding magnetic field displaces plasma electron component, **creating focusing and accelerating electric fields**

Magnetic Vortex Acceleration in Near-Critical Density (NCD) Plasma

Promising choice for source stage: MVA



J. Park, *et al.*, Phys. Plasmas 26, 103108 (2019)
S. Hakimi *et al.*, Phys. Plasmas 29, 083102 (2022)

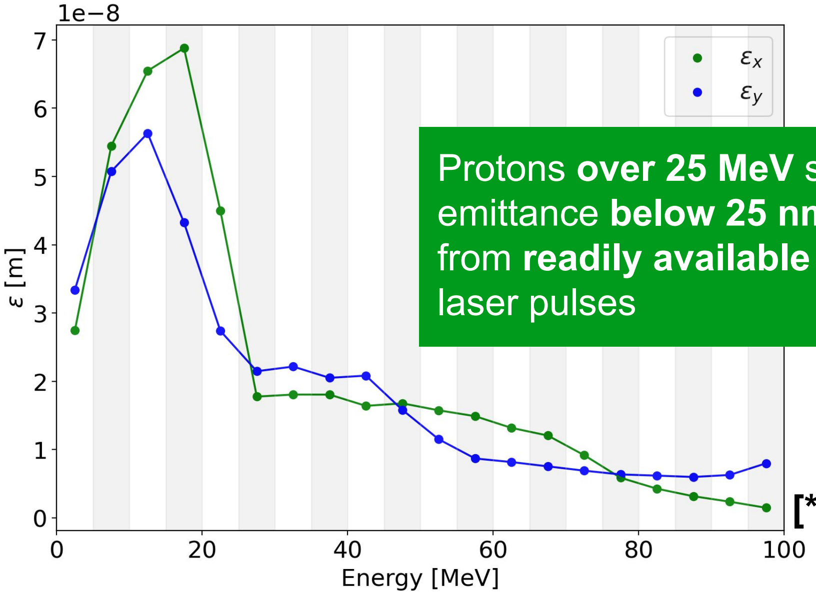
MVA is advantageous in various ways:

- Both **accelerating and focusing fields**
- Ultra-low (nm rad) emittance [*]
- More relaxed geometry due to NCD (µm instead of nm)
- Potential for high rep-rate operation
- Less sensitive to laser contrast

[*] S. Hakimi et al., in preparation (2023)

Magnetic Vortex Acceleration in Near-Critical Density (NCD) Plasma

Promising choice for source stage: MVA



Protons **over 25 MeV** show emittance **below 25 nm·rad** from **readily available** PW laser pulses

[*]

Energy-resolved transverse normalized emittance of MVA proton beam

S. Hakimi *et al*. Laser–solid interaction studies enabled by the new capabilities of the iP2 BELLA PW beamline, *Physics of Plasmas* (2022)

- Ultra-low (nm rad) emittance [*]

[3D3V WarpX PIC sim]
Target density n_e = 2 n_c
Length d = 28 µm
Laser norm. amplitude a_0 = 42
Pulse duration t_L = 42 fs
Central wavelength λ_L = 815 nm

[*] S. Hakimi et al., *in preparation* (2023)

Could MVA Serve as a Mechanism for Plasma-Based Energy Booster Stages?

To answer this, we need to look at the following key issues:

1. Phase Space Acceptance

- What are the **longitudinal & transverse acceptance** of such a stage

2. Beam Injection

- How can an external ion bunch be **transported from source to booste**r and be injected?

3. Charge Transport

- Be able to transport the very **high bunch charges** (> 100 pC) that LPI sources produce

4. Energy Transfer

- Can an **LPI booster** stage have the **same efficiency** as an **LPI source**?

5. Preserve Beam Quality

- **Conserve** ultra-low **emittance** and keep energy spread low

A Hollow-Channel MVA Approach as a Potential Energy-Booster Stage

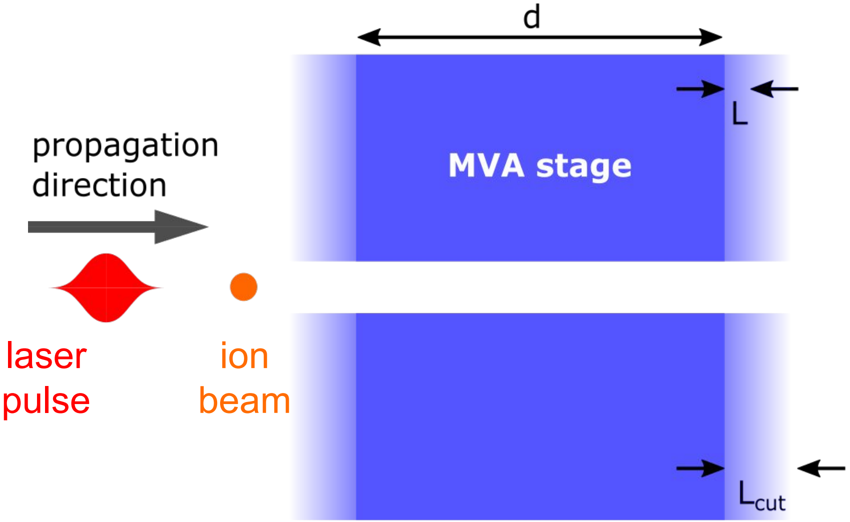
- Traditionally, ions come from **central filament**

⇒ try to suppress MVA for background plasma

⇒ harness accelerating & focusing fields for injected beam

- Our approach: **use hollow channel targets to reduce the interaction between on-axis plasma and beam**
- Hollow channel targets are active research for electron, positron and ion acceleration
- Can possibly created dynamically via laser micromachining

However, choose **laser pulse waist larger than hole radius** to still drive MVA process



A Hollow-Channel MVA Approach as a Potential Energy-Booster Stage

WarpX – open-source particle-in-cell code with advanced algorithms at Exascale

PI: Jean-Luc Vay (LBNL)
>30 contributors internationally

https://ecp-warpx.github.io
L Fedeli, A Huebl et al., *Proc. SC22* (2022)

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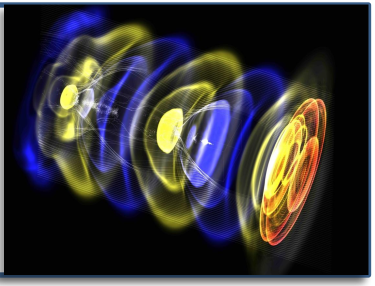
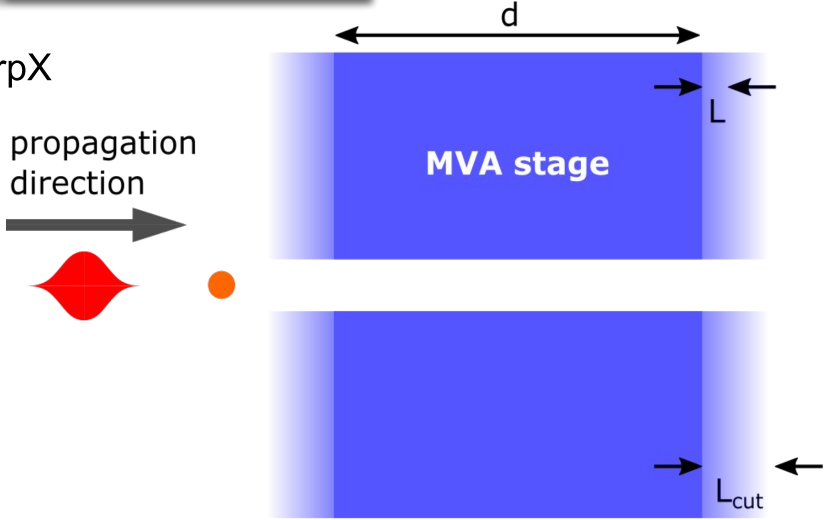


Proof-of-concept 3D3V Particle-in-Cell simulations with WarpX

Simulation Setup Parameters:

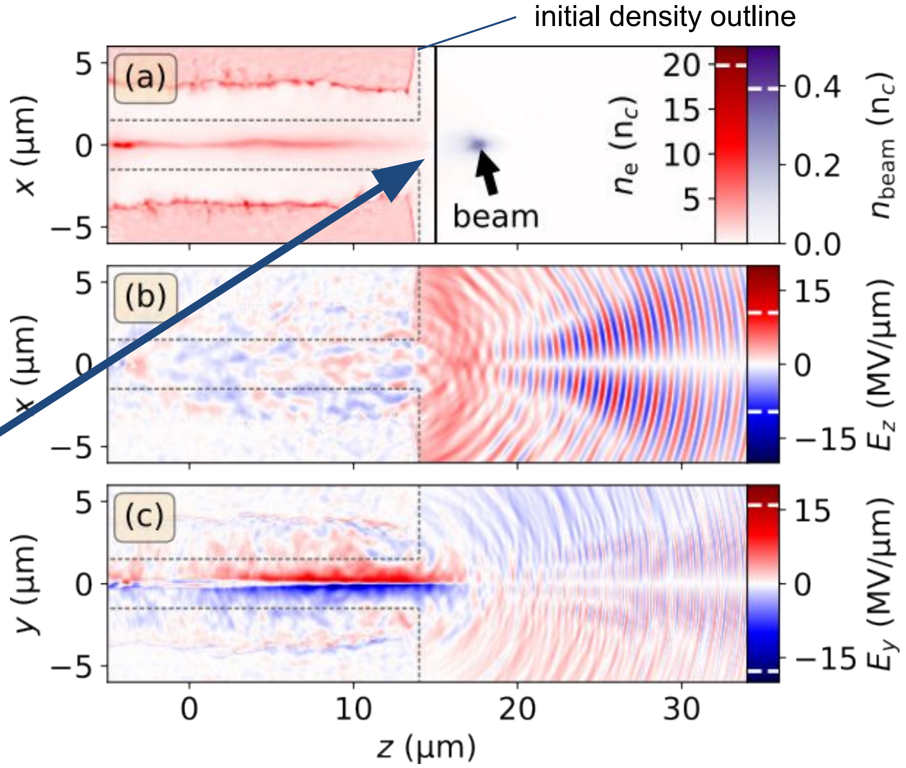
- Target density $n_e = 2\ n_c$
- Length $d = 28$ μm
- Hole radius $r_h = 1.5$ μm
- Laser beam waist $w = 2.12$ μm
- Laser norm. amplitude $a_0 = 42$
- Pulse duration $t_L = 29.8$ fs
- Central wavelength $\lambda_L = 815$ nm

BELLA iP2



MVA-Typical Field Structures also Exist for Hollow Scheme

- With a pre-inscribed hole, we observe that the MVA mechanism holds
  - Electron filament (a)
  - Accelerating fields (b)
  - Focusing fields (c)
- Region of highest sustained acc. field about 1µm behind channel exit
- Drive laser pulse always overtakes proton beam for non-relativistic β

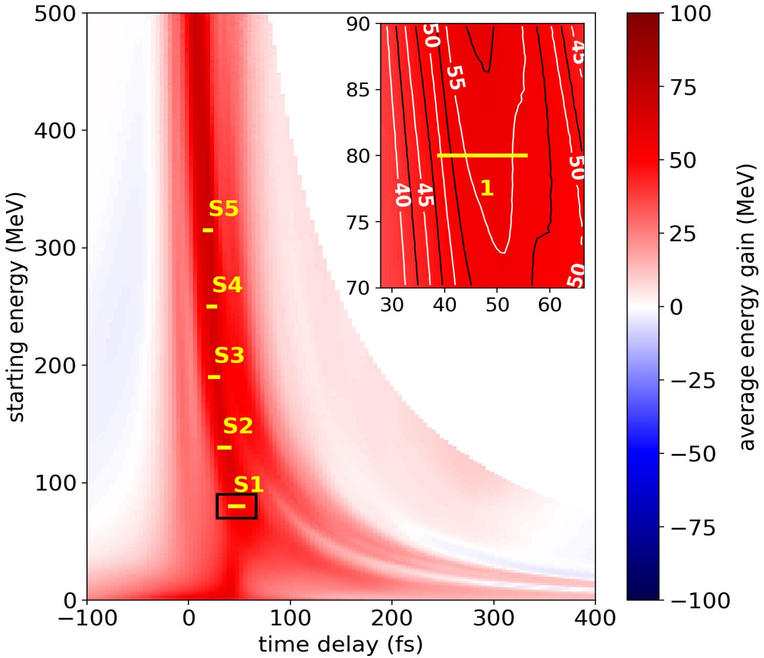


M. Garten et al., arXiv:2308.04745 (2023)

Longitudinal Acceptance Allows for Broad Boosting Range

1. Phase Space Acceptance ✅ Longitudinal

- **Same stage concept suitable for wide range of initial energies, bridging over the mid-beta regime**
- Approx. flat accelerating region for same wide range of initial energies
  - General acceleration seen for over 300 fs delay range
  - In yellow: 15 fs of near flat maximum acceleration (55 – 80 MeV)



Temporal delay vs. driving laser pulse determines boost:

Tracking of non-interacting protons through hollow MVA stage

M. Garten et al., arXiv:2308.04745 (2023)

Accepted Transverse Emittance Increases for Higher Initial Energies

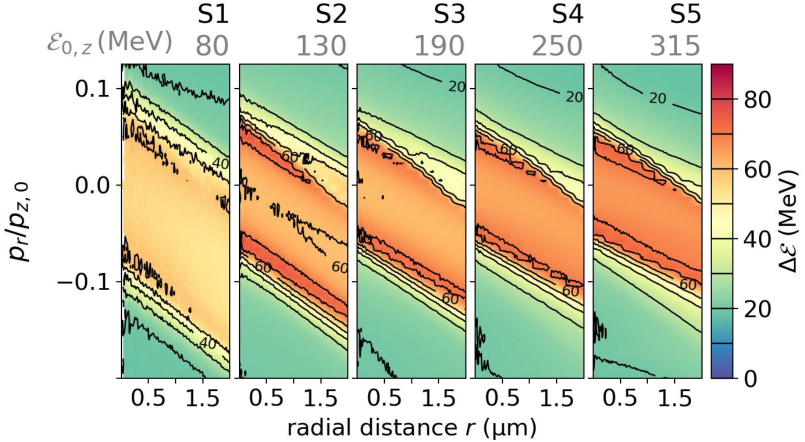
1. Phase Space Acceptance ✅ Transverse

- Very broad transverse acceptance for small boosts of,e.g., 20 MeV
  - Sufficient accepted emittance for LPI sources
  - Fairly homogeneous maximum boost region
- Accepted normalized emittance becomes larger for higher initial energies

$$\epsilon_n = (p_z/mc)\left[\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle\right]^{1/2}$$

$$x' = p_x/p_z$$

M. Garten et al., arXiv:2308.04745 (2023)



Tracking non-interacting protons for five example beams with fixed p_z and varying transverse momenta p_r

	S1	S2	S3	S4	S5
$\Delta\mathcal{E}$ 30 MeV	29.0	33.0	35.2	39.5	44.3
40 MeV	25.9	29.2	30.0	32.3	34.9
50 MeV	22.7	26.0	26.2	28.8	31.5
60 MeV	1.3	20.7	24.4	26.9	29.4

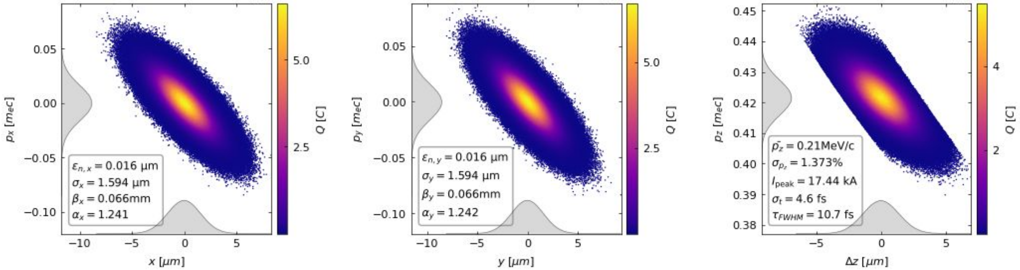
$[\epsilon_n]$ = nm·rad

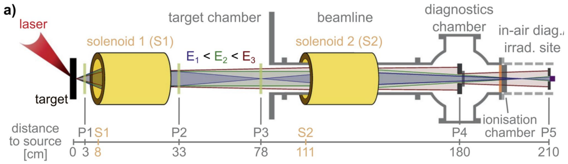
Ultra-Intense Beam Transport Is Being Actively Researched in the Community

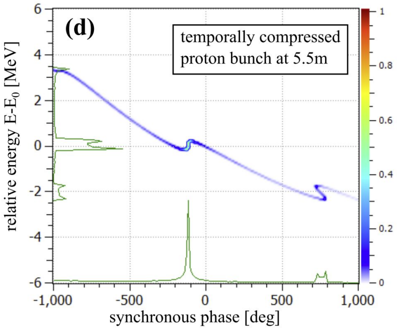
2. Injection of External Beam (✓)

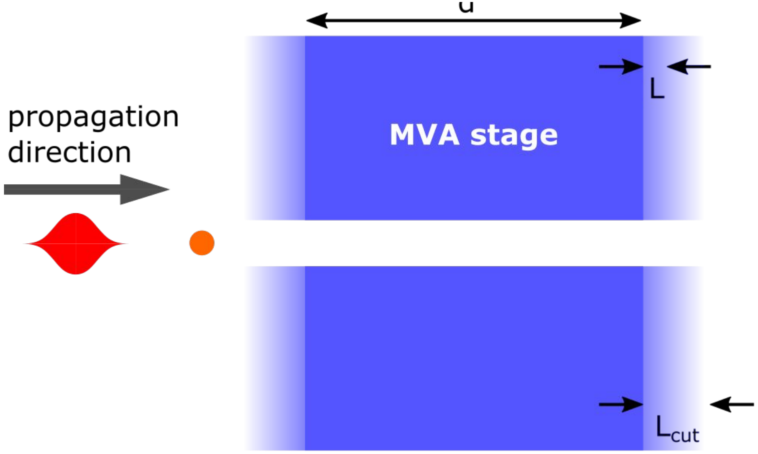
1. Energy selection from LPI source
2. Potentially phase space rotation between stages

Phase space rotated proton bunch for WarpX simulation input









[1] Brack, F.-E., et al. *Scientific Reports*, *10*(1), 9118 (2020)

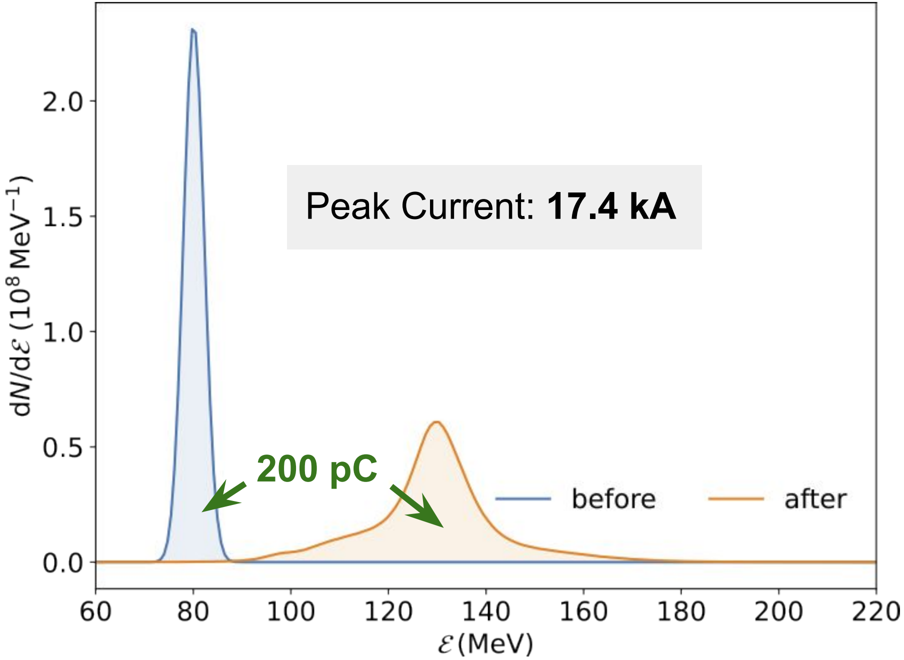
[2] Busold, S., et al. *IPAC Proceedings* (2014)

Realistic Beam Charges Can Be Transported & Boosted

3. Charge Transport ✅

- **200 pC of charge fully transported and boosted**

Fully self-consistent 3D WarpX simulation with space charge



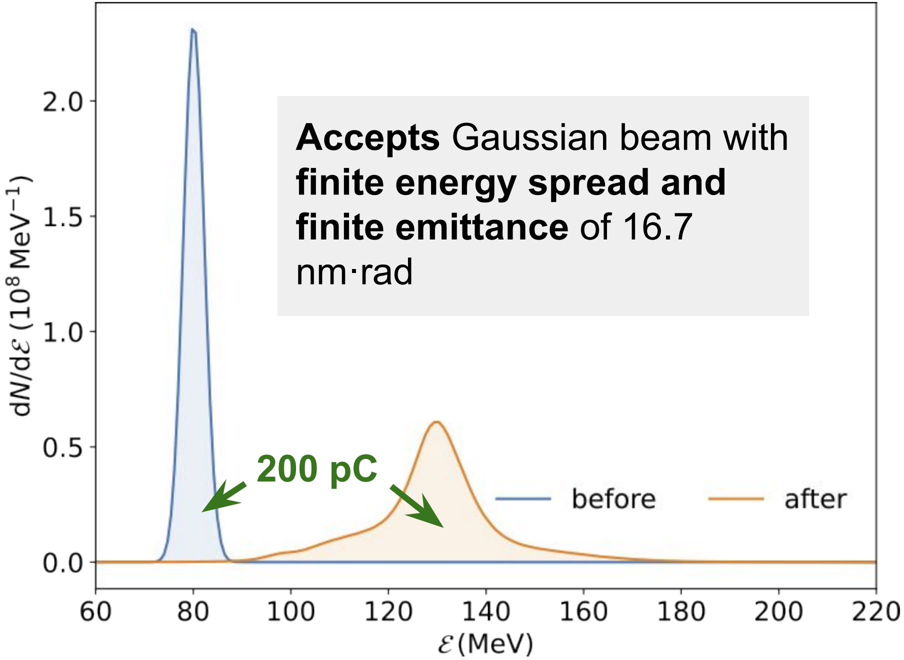
M. Garten et al., arXiv:2308.04745 (2023)

Realistic Beam Charges Can Be Transported & Boosted

4. Energy Transfer ✅

- 200 pC of charge fully transported and boosted
- **Boost by 50 MeV as expected from tracking simulations**

Fully self-consistent 3D WarpX simulation with space charge



Accepts Gaussian beam with **finite energy spread and finite emittance** of 16.7 nm·rad

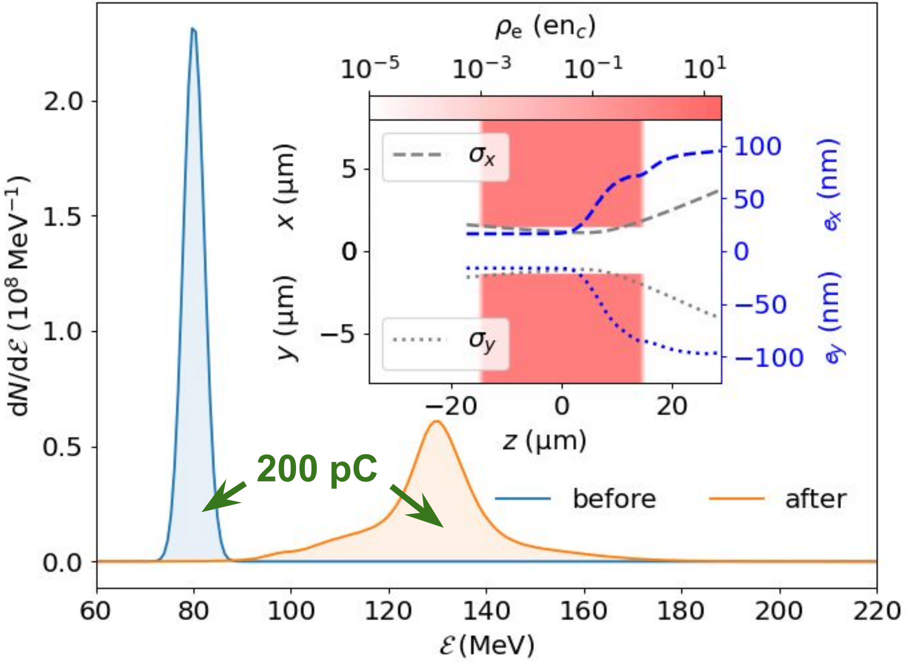
M. Garten et al., arXiv:2308.04745 (2023)

Realistic Beam Charges Can Be Transported & Boosted

5. Preserve Beam Quality ✅

- 200 pC of charge fully transported and boosted
- Boost by 50 MeV as expected from tracking simulations
- **Emittance still below 100 nm·rad**
- Ample opportunity for optimization

Fully self-consistent 3D WarpX simulation with space charge



M. Garten et al., arXiv:2308.04745 (2023)

WarpX: conceived & developed by a multidisciplinary, multi-institution team

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NNSA National Nuclear Security Administration

BERKELEY LAB

Jean-Luc Vay (ECP PI)

Arianna Formenti

Marco Garten

Axel Huebl

Rémi Lehe

Ryan Sandberg

Olga Shapoval

Yinjian Zhao

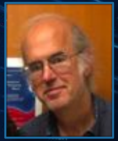
Edoardo Zoni

ATAP ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

BLAST BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

Ann Almgren (ECP coPI)

John Bell



Kevin Gott (NESAP)

Junmin Gu

Revathi Jambunathan

Hannah Klion

Prabhat Kumar

Andrew Myers

Weiqun Zhang

AM CRD AMReX

NERSC NESAP

David Grote (ECP coPI)

+ a growing list of contributors from labs, universities…

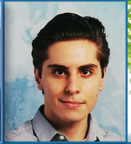
DE LA RECHERCHE À L'INDUSTRIE cea PARIS-SACLAY

(France)

Henri Vincenti

Luca Fedeli

Thomas Clark



Neïl Zaim

Pierre Bartoli

DESY.

(Germany)

Maxence Thévenet

Alexander Sinn

SLAC

Marc Hogan (ECP coPI)

Lixin Ge

Cho Ng

CERN

(Switzerland)

Lorenzo Giacomel

…& private sector

MODERN ELECTRON

Intense Computing

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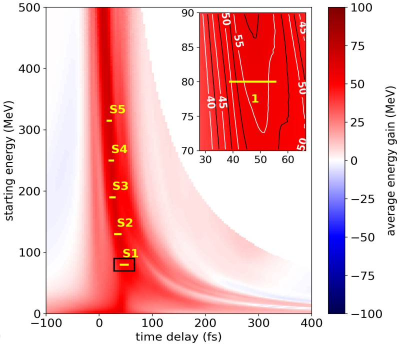
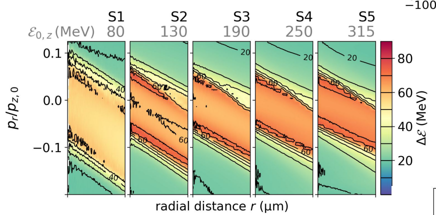
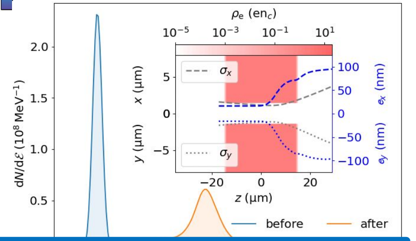
Summary & Conclusion

- Demonstrated **novel hollow-channel MVA** scheme for **boosting** ion bunches from LPI sources **to relativistic regime** in 3D PIC simulations
- **Readily available PW laser facility parameters** suffice for **both source and booster** stages
- Robust mechanism, **scalable to arbitrary initial energies**, potential way to stage to relativistic energies
- Space-charge dominated proton beam from LPI source can be **boosted without charge loss**

M. Garten et al., [arXiv:2308.04745](https://arxiv.org/abs/2308.04745) (2023)







Phase Space Acceptance ✅	**Beam Injection** (✓)
Energy Transfer ✅	**Preserve Beam Quality** ✅
Charge Transport ✅	

Thank you for your attention!