Quality-preserving laser-plasma ion beam booster via hollow-channel magnetic vortex acceleration

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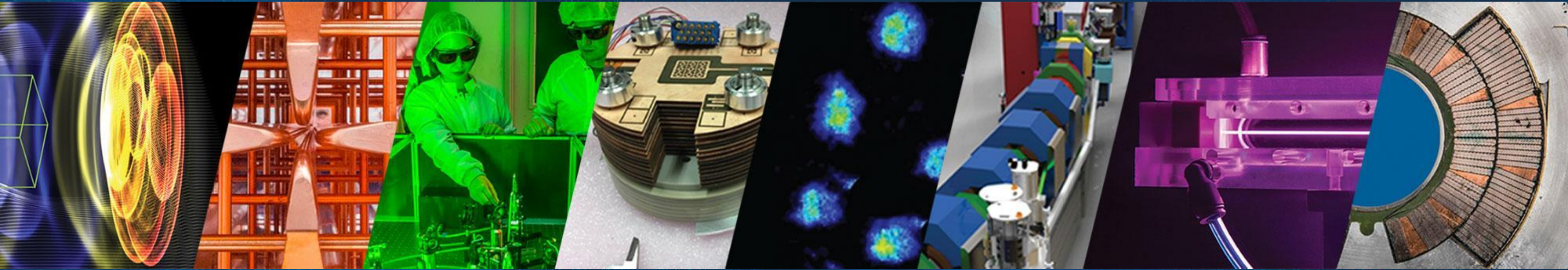
PRR accepted



2024/07/25

Advanced Accelerator Concepts Workshop 2024 (AAC'24)

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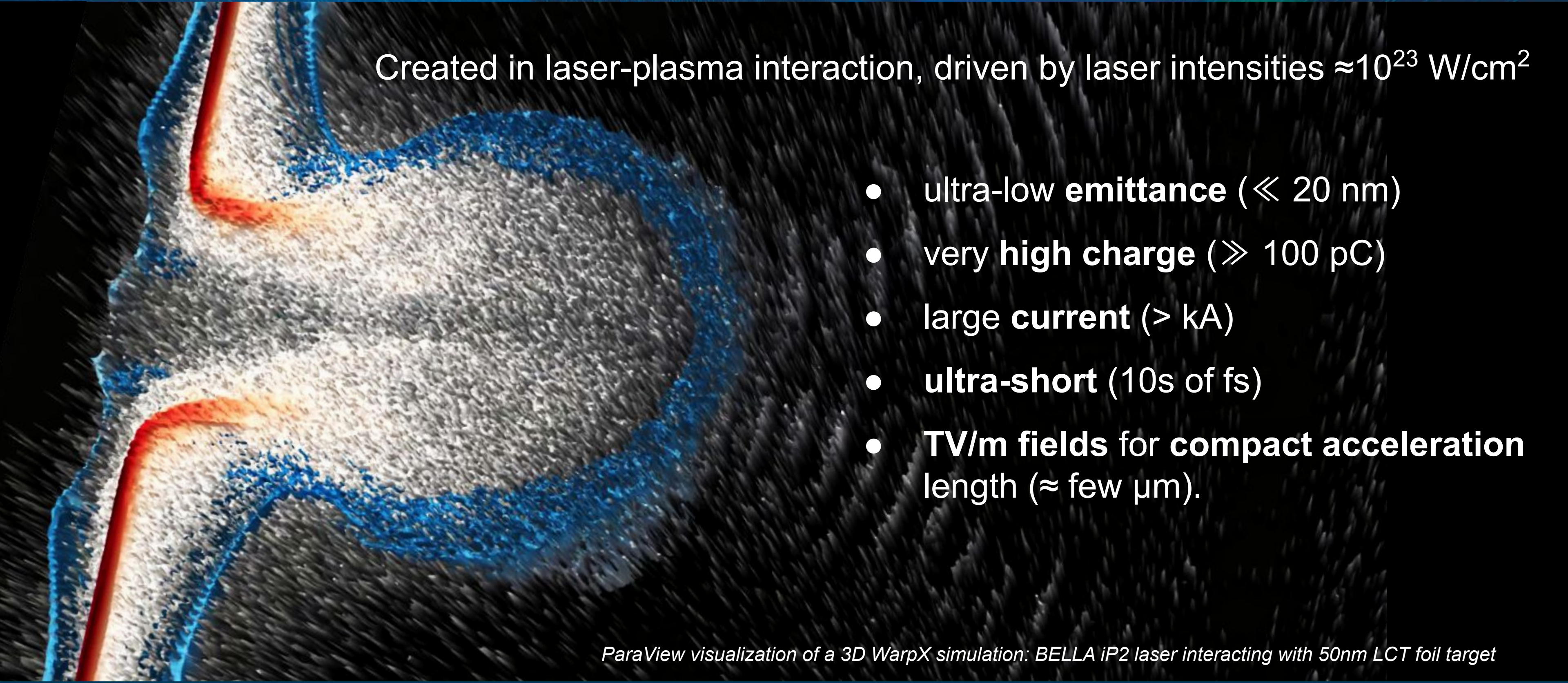
LPI Sources: Unique Ion Bunches for Applications



Created in laser-plasma interaction, driven by laser intensities ≈10^{23} W/cm^2

- ultra-low **emittance** ($\ll$ 20 nm)
- very **high charge** ($\gg$ 100 pC)
- large **current** (> kA)
- **ultra-short** (10s of fs)
- **TV/m fields** for **compact acceleration** length (≈ few μm).

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

Relativistic Ion Energies: Significantly Harder than for Electrons

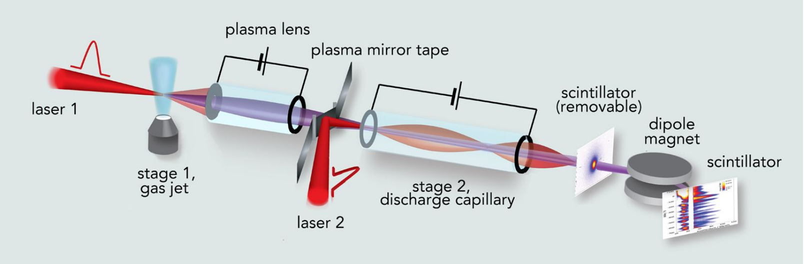
- Laser-ion acceleration **remains an indirect process**

  … even with current short-pulse PW laser facilities
- Current energy records **60-150 MeV/u** [1-4]

  ⇒ fall just short of energies for, e.g., radiation oncology
- Many applications **want high charge at high energies**

  … mechanisms often provide exponential spectrum

Staged approach could be a solution



S. Steinke *et al.*, Nature (2016)

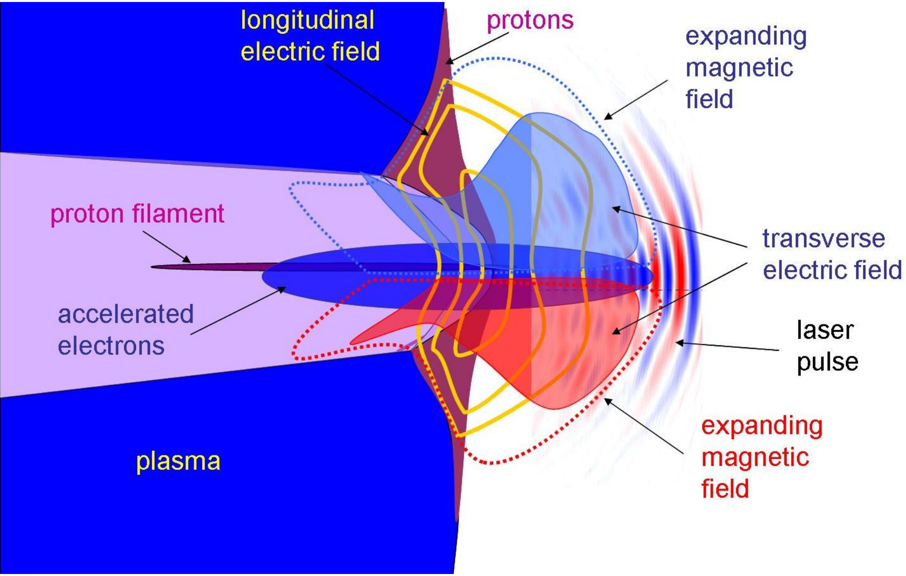
- Successfully demonstrated for laser-electron acceleration

  but reaching **relativistic ion energies** is a **significantly harder problem**

[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). *Nat Commun*, *9*(1), 724., [4] Ziegler, T. et al. (2024). *Nat Phys* 20, 1211–1216 (2024)

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)

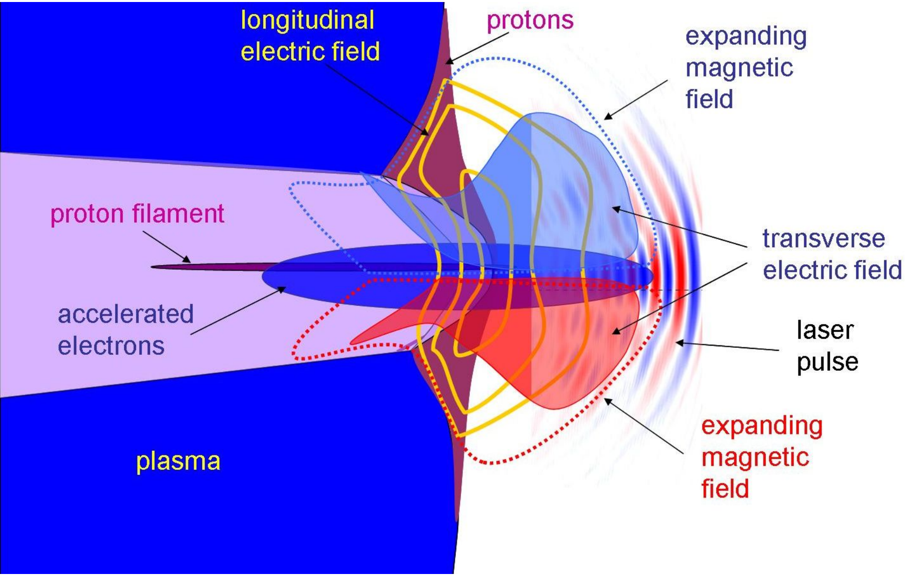
Reviewing the mechanism

- 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**

Talk WG2 Mon. 07/22 S. Bulanov

Advantages of MVA for Staging

Promising choice for source stage: MVA



J. Park, *et al.*, Phys. Plasmas 26, 103108 (2019)
S. Hakimi *et al.*, Phys. Plasmas 29, 083102 (2022)
[*] S. Hakimi et al., in preparation (2024)

MVA is advantageous in various ways:

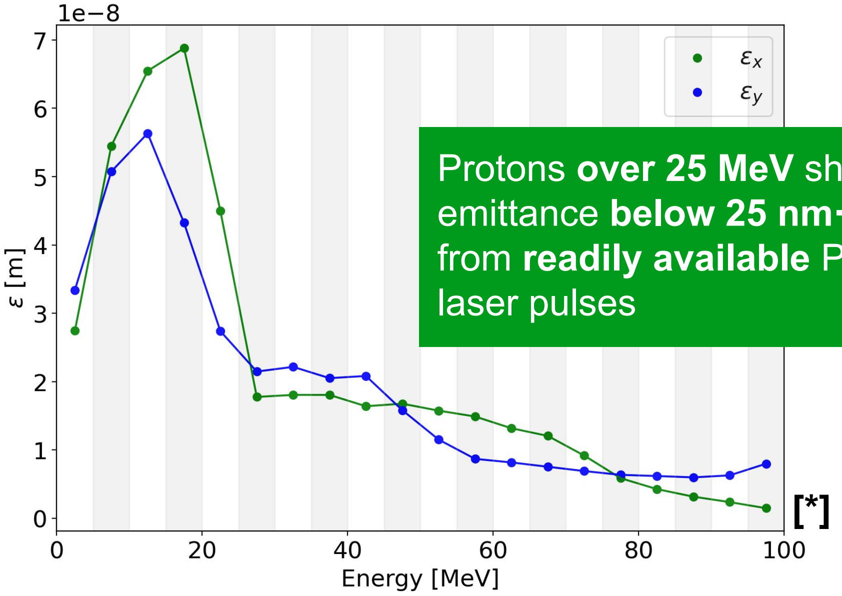
- Both **accelerating and focusing fields**
- Ultra-low (nm rad) emittance [*]
- More relaxed geometry due to NCD (μm instead of nm)
- Potential for high rep-rate operation
- Less sensitive to laser contrast

At BELLA iP2, first experimental campaigns exploring MVA as a source have been performed

Poster WG2 Mon. 07/22 A. McIlvenny

High-Energy Protons from MVA Show Ultra-Low Emittance

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* (2024)

Can MVA Serve in Plasma-Based Energy Boosters?

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 does an external ion bunch need to be **shaped in phase space** to be injected?

3. Charge Transport

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

4. Energy Boost

- Can an **LPI booster** stage increase bunch energy by as much 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

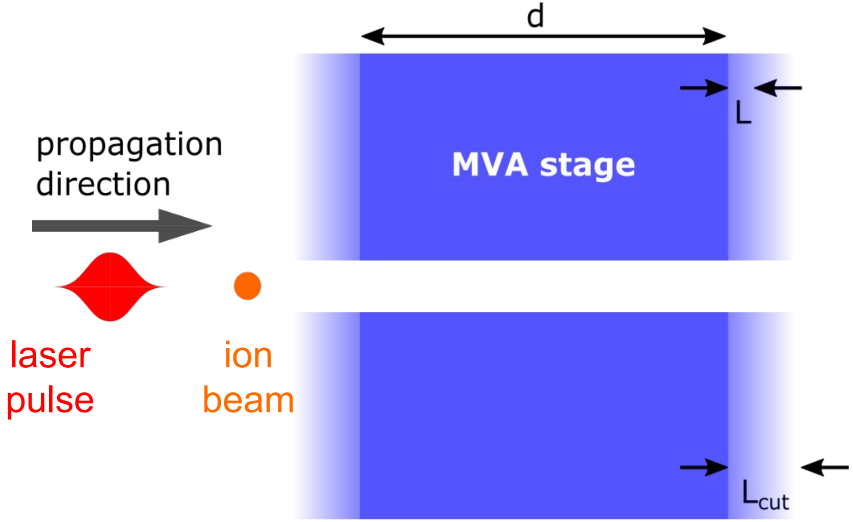
- Traditionally, ions come from **central filament**

⇒ try to suppress MVA for background plasma

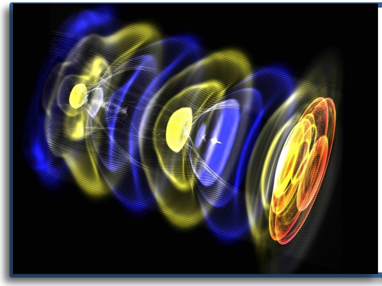
⇒ harness accelerating & focusing fields for injected beam

- 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 be created dynamically via laser micromachining

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



Self-Consistent Modeling with 3D3V WarpX Simulations



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

Awarded the 2022 Gordon-Bell Prize of Supercomputing

https://ecp-warpx.github.io

L Fedeli, A Huebl et al., *Proc. SC22* (2022)

✨NEW✨ now under open governance

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ECP EXASCALE COMPUTING PROJECT

THE LINUX FOUNDATION

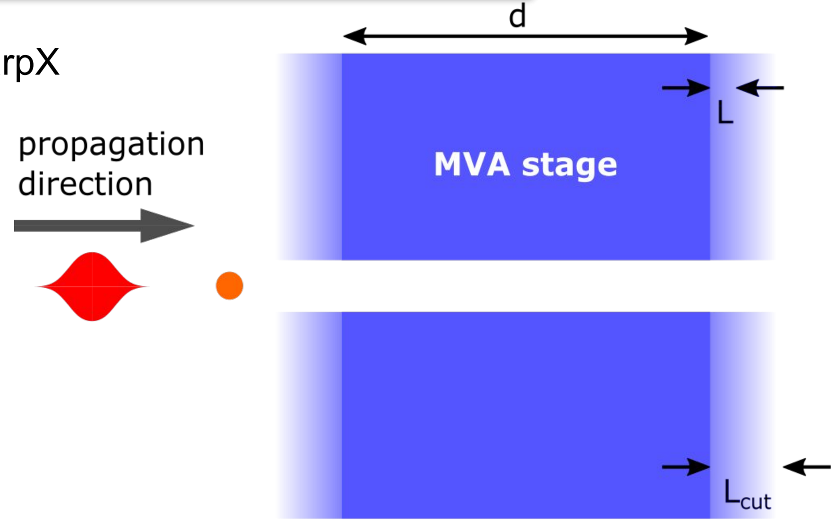
HIGH PERFORMANCE SOFTWARE FOUNDATION

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

Simulation Setup Parameters:

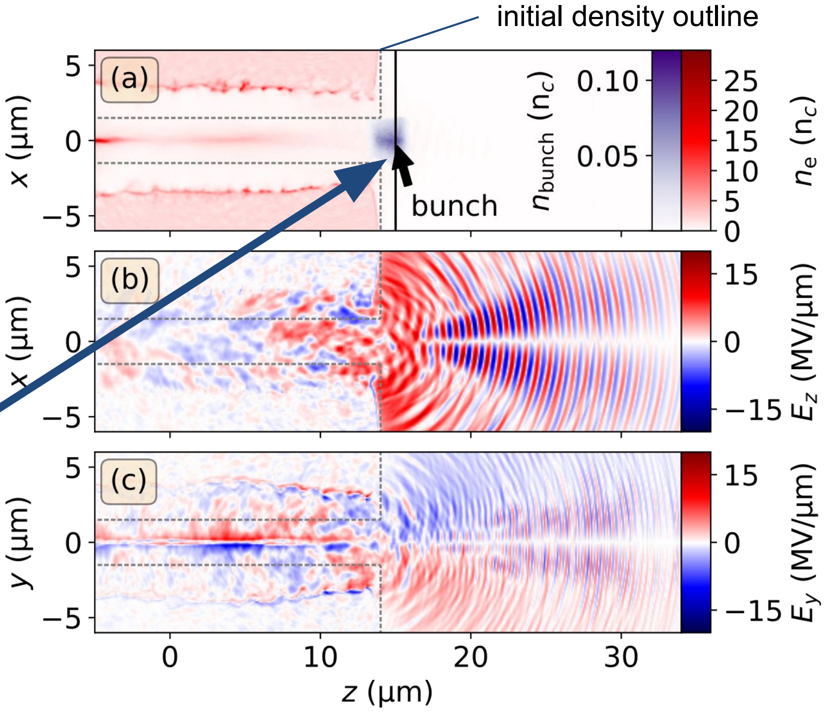
- Target density $n_e = 2\ n_c$
- Length $d = 28\ \mu m$
- Hole radius $r_h = 1.5\ \mu m$
- Laser beam waist $w = 2.12\ \mu m$
- Laser norm. amplitude $a_0 = 42$
- Pulse duration $t_L = 29.8\ fs$
- Central wavelength $\lambda_L = 815\ nm$

BELLA iP2



MVA-Typical Field Structures also Exist for Hollow Scheme

- With a pre-inscribed hole, we observe that the MVA mechanism still exhibits
    - Central 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

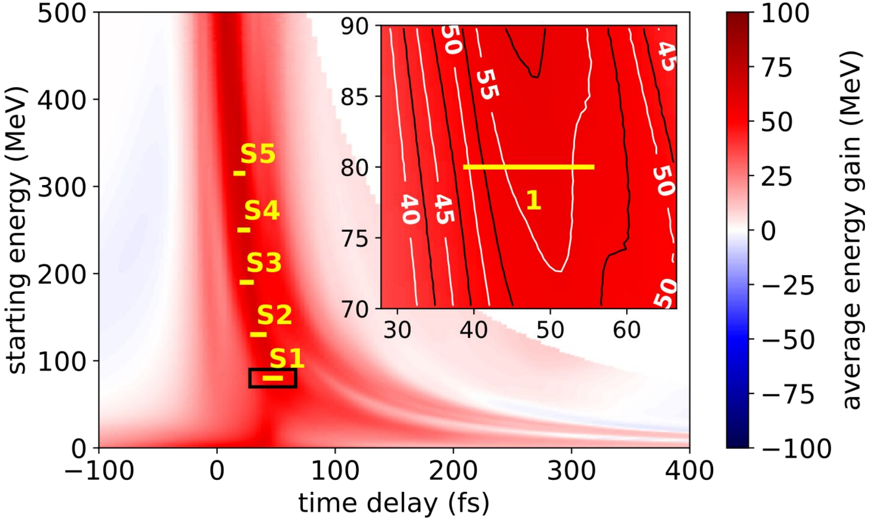


M. Garten et al., arXiv:2308.04745 (2023), accepted to PhysRevResearch (2024)

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 to PhysRevResearch (2024)

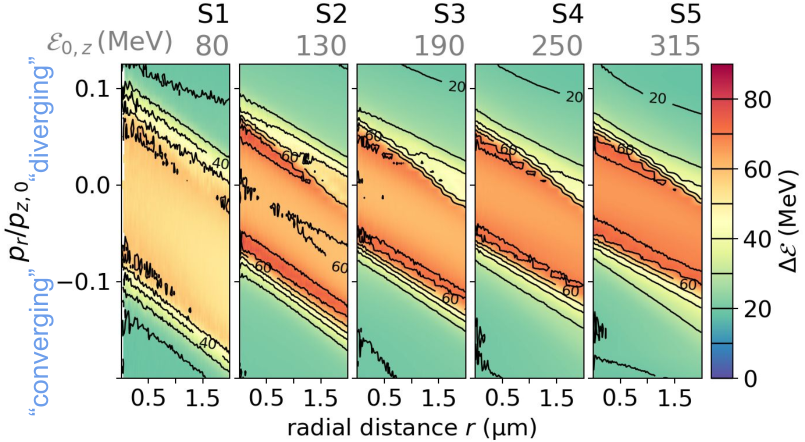
Accepted Transverse Emittance Increases for Higher Initial Energies

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

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

$$x' = p_x/p_z$$



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

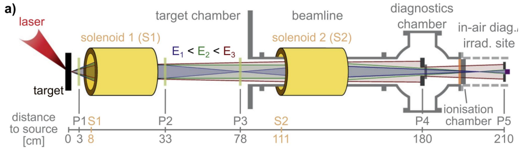
M. Garten et al., arXiv:2308.04745 (2023), accepted to PRR (2024)

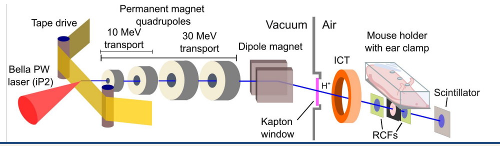
Ultra-Intense Beam Transport Is Being Actively Researched in the Community

2. Injection of External Beam

(✓)

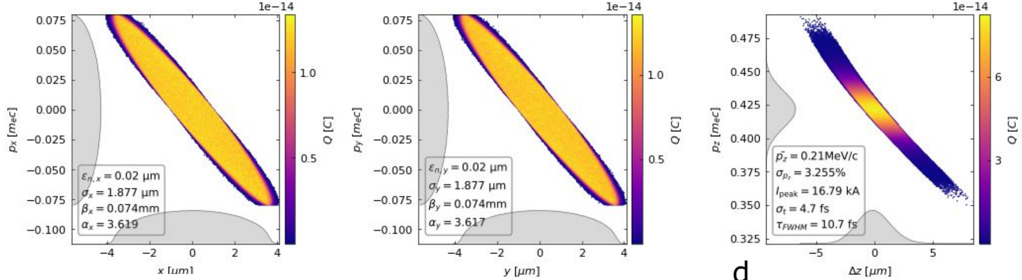
1. Energy selection from LPI source
2. Potentially phase space rotation between stages

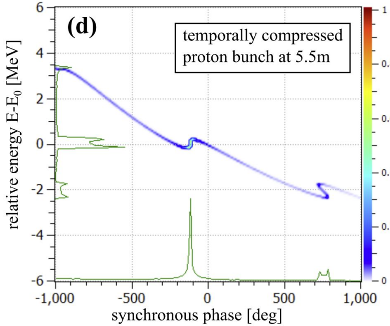


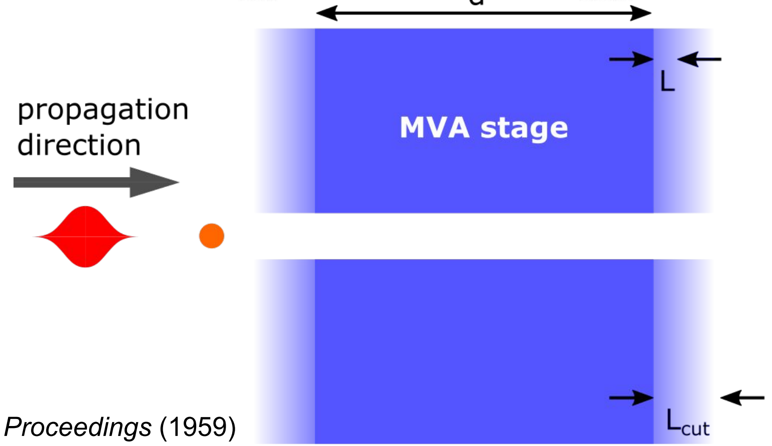


Talk WG2 Tue. 07/23 J. DeChant

Phase space rotated KV [3] proton bunch for WarpX simulation input







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

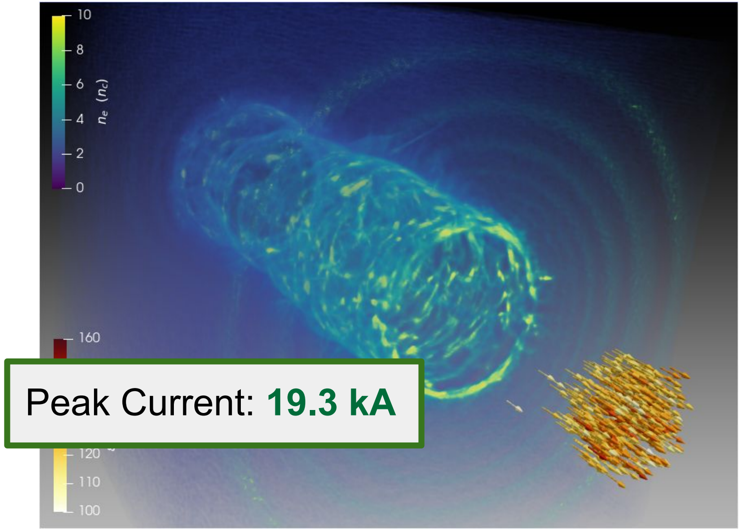
[2] Busold, S., et al. *IPAC Proceedings* (2014)

[3] Kapchinskij & Vladimirskij, *HEACC Proceedings* (1959)

Realistic Beam Charges Can Be Transported

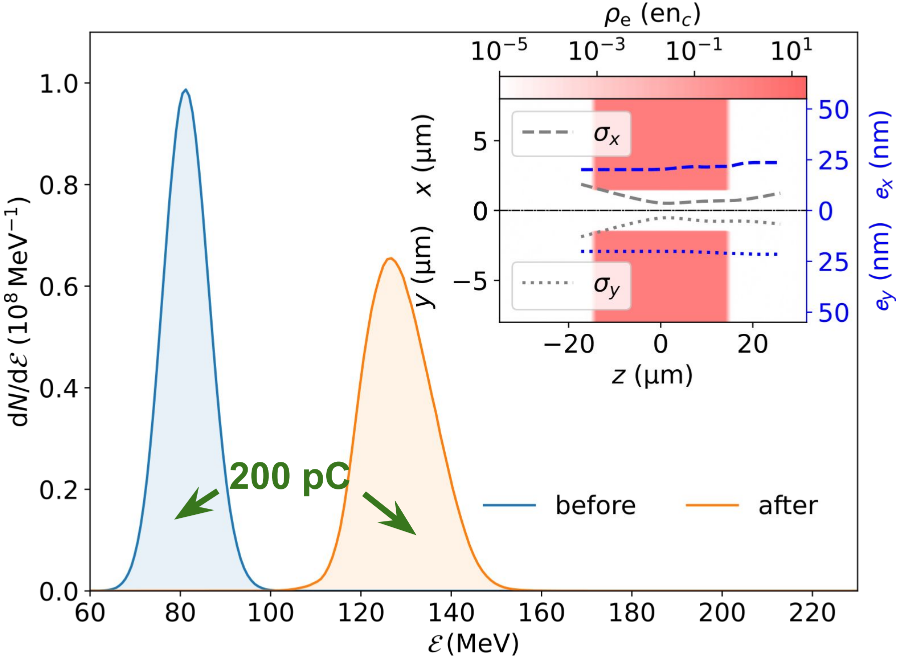
3. Charge Transport ✅

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



Peak Current: **19.3 kA**

Fully self-consistent 3D WarpX simulation with space charge



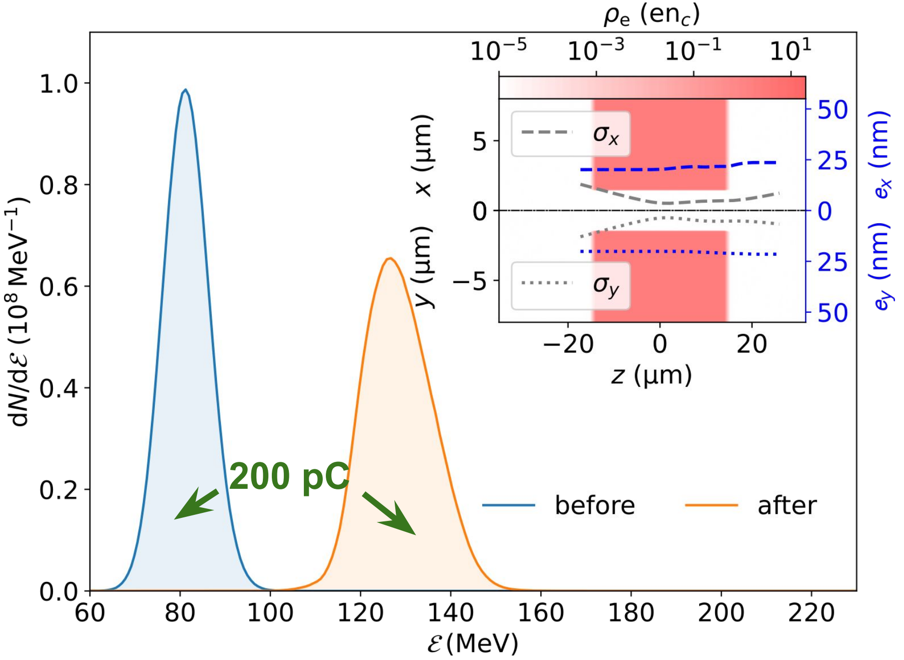
M. Garten et al., arXiv:2308.04745 (2023), accepted to PRR (2024)

Realistic Beam Charges Can Be Transported & Boosted

4. Energy Boost ✅

- 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



M. Garten et al., arXiv:2308.04745 (2023), accepted to PRR (2024)

Realistic Beam Charges Can Be Transported & Boosted

5. Preserve Beam Quality ✅

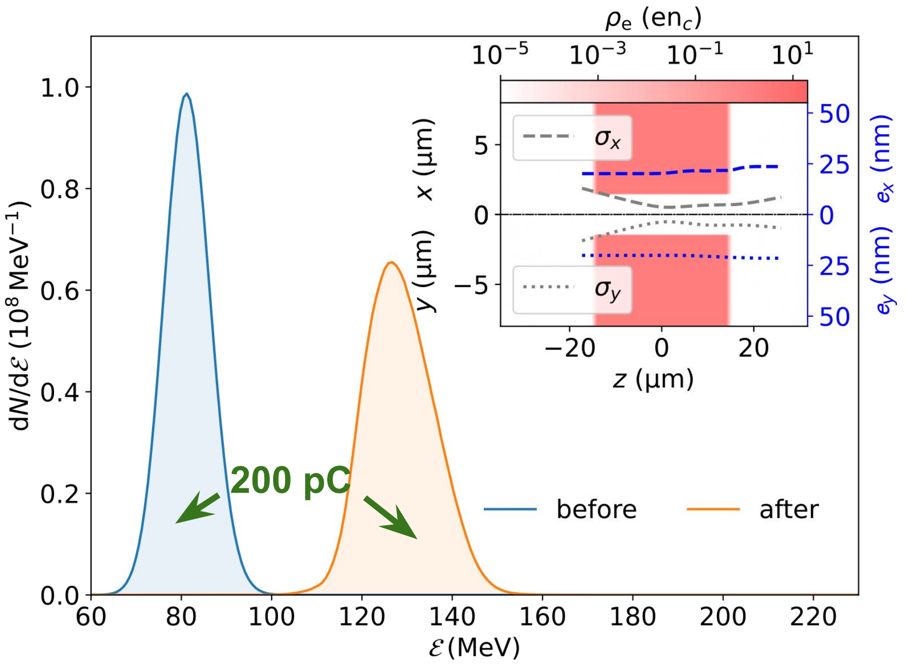
- 200 pC of charge fully transported and boosted
- Boost by 50 MeV as expected from tracking simulations
- **Emittance increased by only 3.5 nm**

❖ Energy spread: **from 5% to 7%**

❖ Norm. emittance: **from 20 nm to 23.5 nm**

❖ Ample design space for optimization!

Fully self-consistent 3D WarpX simulation with space charge



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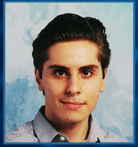

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DARPA ECP EXASCALE COMPUTING PROJECT BELLA LaserNetUS

Summary & Conclusion

PRR accepted, arXiv:2308.04745 (2023)

- ✅ Demonstrated **novel hollow-channel MVA** scheme
- ✅ **Boost** ion bunches of **arbitrary β**
- ✅ Scalable **to relativistic regime** via the **same stage**
- ✅ **Charge**, **energy spread**, and **emittance** are **conserved well**
- ✅ **State-of-the-art PW laser** facility parameters are **sufficient**

Thank you for your attention!