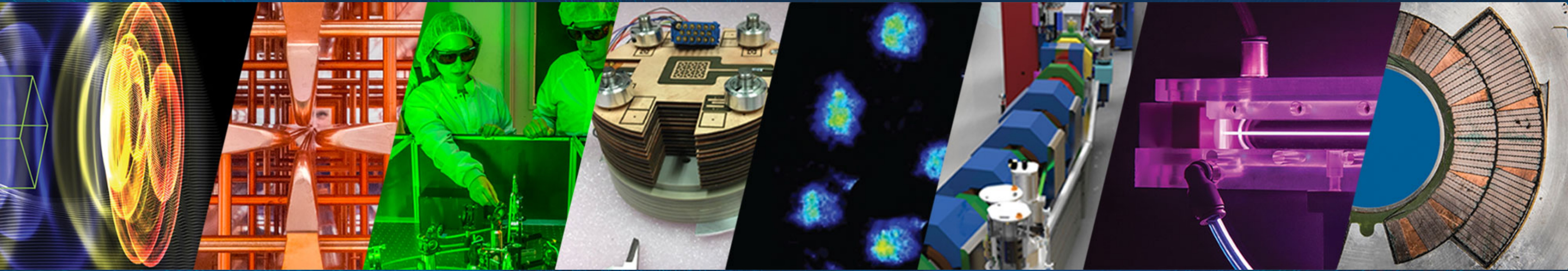
# A mid-beta booster for proton beams

Accelerator Technology & Applied Physics Division



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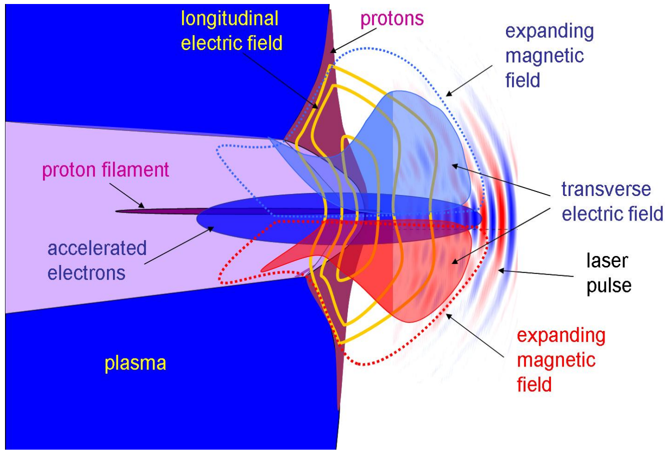
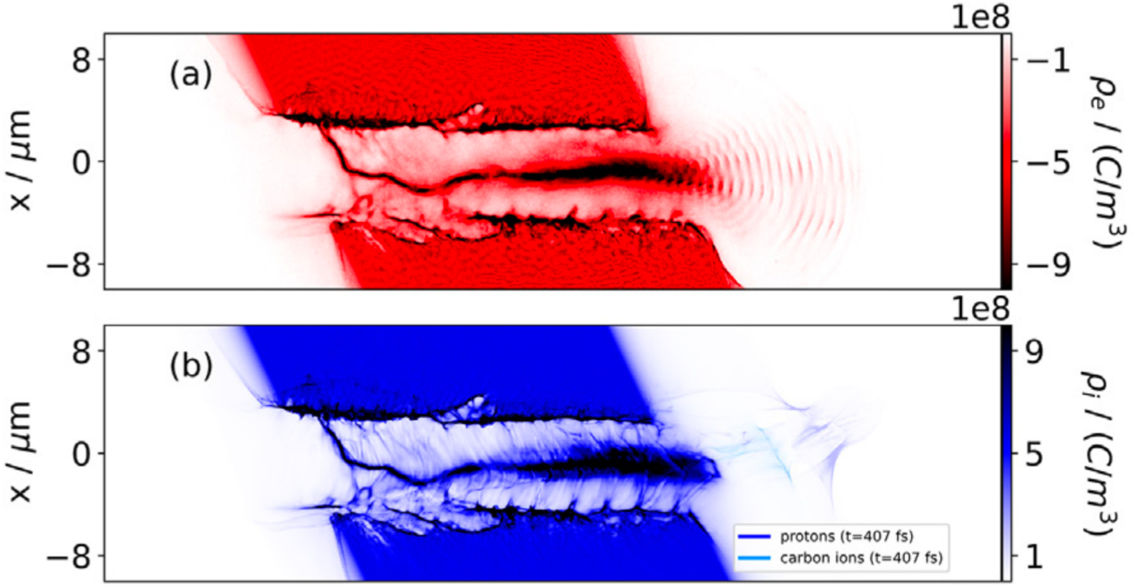
# Outline

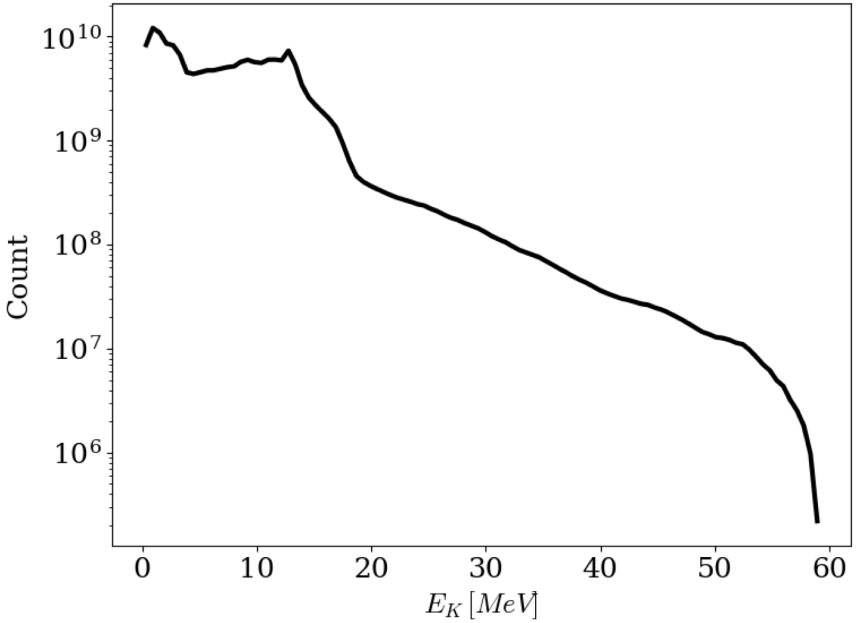
- Motivations
- Physics of the snowplow acceleration
- Simulation results
- Increase the energy gain: density tapering

# MVA acceleration enables production of 10s MeV proton beams

MVA acceleration regime can be achieved with BELLA-like experimental conditions ($\mathcal{E}_L \simeq 20 - 40J, w_0 \simeq 4\mu m$)




Simulations show production of low emittance and low divergence proton beams up to $\sim 60 MeV$ using BELLA-like parameters. Analysis of experiments is ongoing.

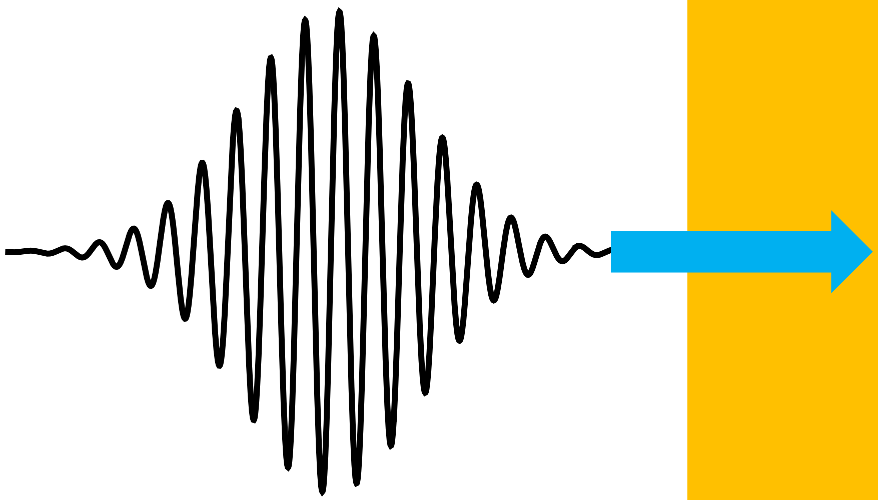
**Can we increase the energy to $\gtrsim GeV$?**

[Park et al., POP, 2019, Hakimi et al, POP, 2020]

# Propagation in near-critical density targets slows down laser pulse

Protons are non relativistic ($\beta < 1$), so we need to slow down the laser pulse that drives the accelerating field

$$n_0 > n_c$$



High intensity laser pulse can propagate in overcritical density (i.e., relativistic transparency)

$$n_c[10^{21} cm^{-3}] \simeq \frac{1.12}{\lambda_0[\mu m]^2}$$

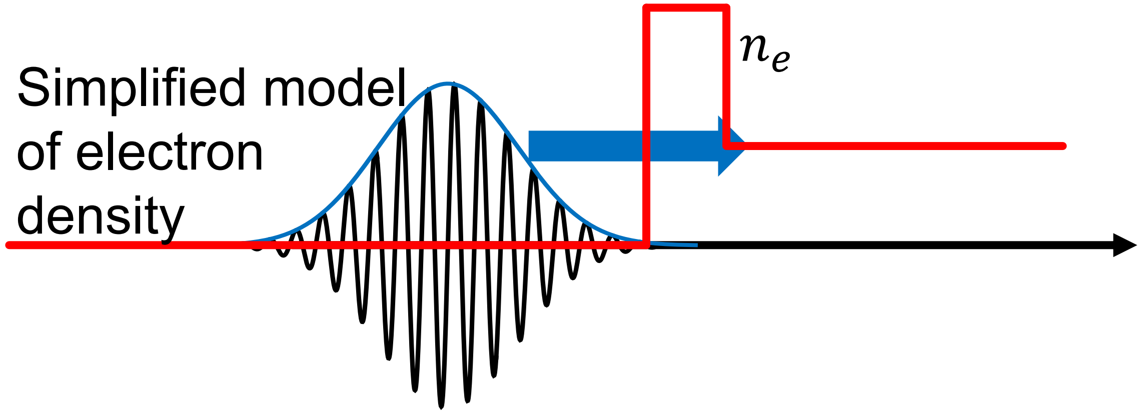
Relativistic transparency

$$\beta_g \simeq \sqrt{1 - \frac{n_0}{n_c}} \longrightarrow \beta_g \simeq \sqrt{1 - \frac{n_0}{\gamma n_c}}$$

From simulations we computed $\beta_g \sim 0.8$ for parameters relevant for the snowplow ($n \sim 2 - 5\, n_0, \mathcal{E}_L \sim 100 - 400\, J$)

[Liu et al., PPCF, 2020]

# The electric field created by the density spike can reach 10s TV/m



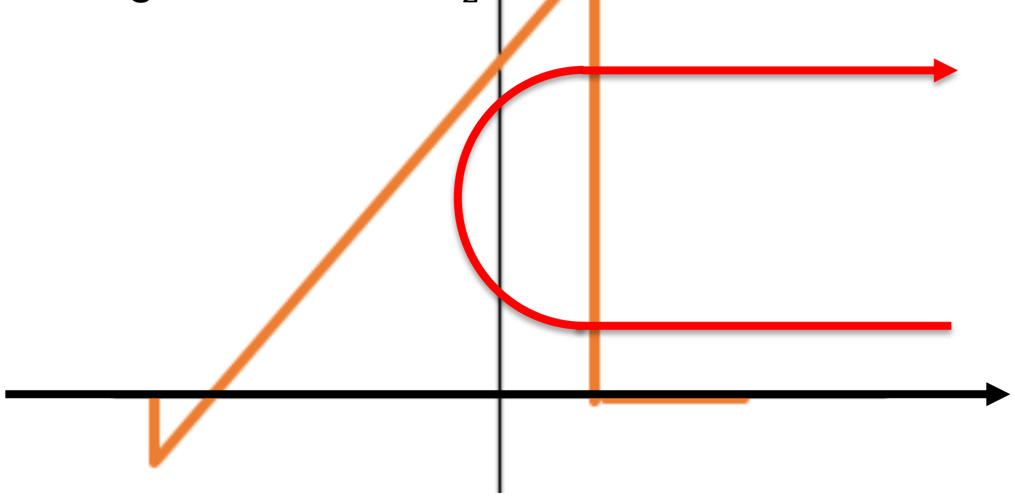

The ponderomotive force (radiation pressure) pushes the electrons forward until an electrostatic field counterbalances it

$$\partial_\xi E_z = qk_p \frac{\beta_g}{\beta_g - \beta_i(\xi)}$$
$$n_i(\xi) = \frac{\beta_g}{\beta_g - \beta_i(\xi)}$$
$$\partial_\xi \beta_i = -\frac{q}{m}\frac{E_z(\xi)k_p}{\beta_g - \beta_i(\xi)}$$

Equations for full electron depletion in quasistatic approximation

[Shorokhov and Pukhov, 2004; Liu et al., PRL, 2022]

The field structure moves with the laser at $\beta_g$

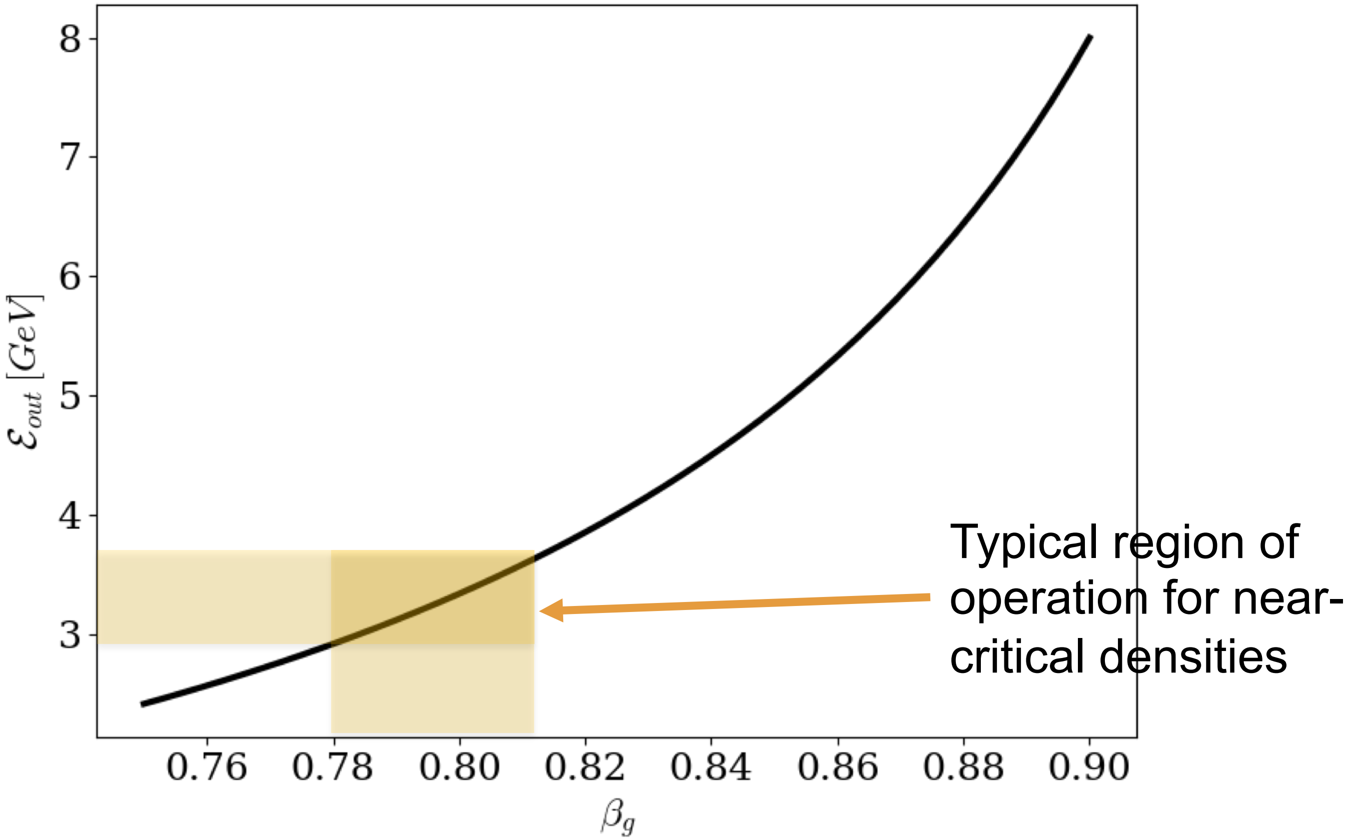



When the laser pulse completely expels the electrons

$$E_{MAX} \approx \frac{\pi}{2}\sqrt{\frac{m_p}{m_e}}E_0 = 67E_0 \sim 10s\ TV/m$$

The trapping threshold for protons is $\beta_i < \beta_g$ due to the finite extent of the accelerating field

# Snowplow field enables proton acceleration up to GeV energies

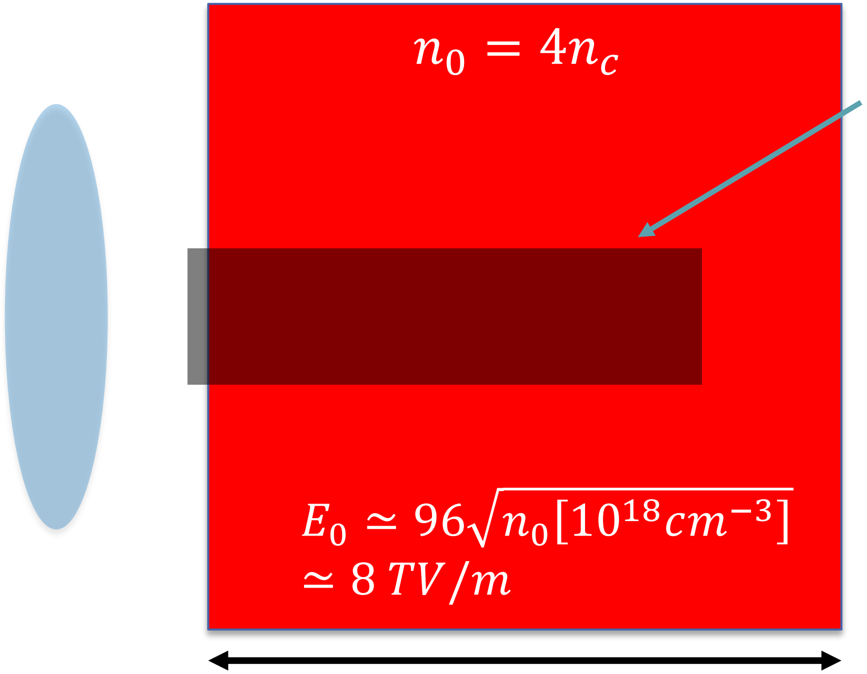



$$\mathcal{E}_{out} = \gamma_g^2\left[\gamma_s\left(1+\beta_g^2\right) - 2p_s\beta_g\right] \rightarrow 2\gamma_g^2\beta_g^2$$

In the limit of $a_0 \gg 1$ (i.e., when the laser can trap background protons, $p_s \rightarrow 0$), the snowplow acceleration is analogous to a relativistic moving mirror.

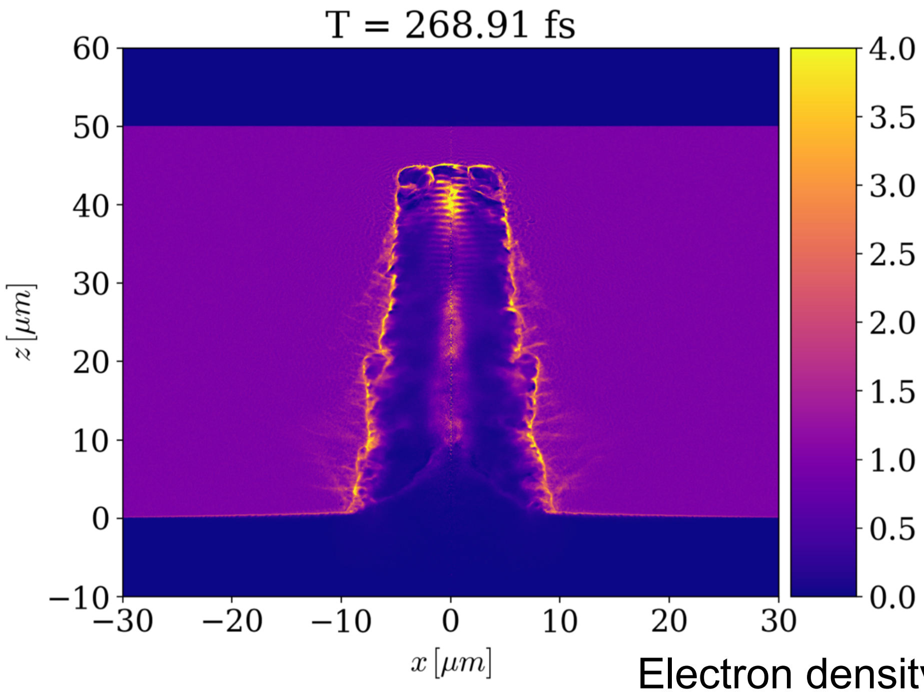
The laser energy required to trap protons is lowered if the protons are pre-accelerated in a previous stage. We are currently exploring the transport and post-acceleration to $\sim GeV$ energies of protons generated in an MVA stage.

# In simulations we analyze the dynamics of test protons in the snowplow




$50\mu m$

Test protons to study phase space of trapped particles




Electron density

$a_0 = 100$
$w_0 = 4\mu m$
$T_{FWHM} = 35\,fs$
$\mathcal{E}_L \simeq 400\,J$

Circular pol.

Focused on target center

Simulations are performed using azimuthal decomposition (quasi-3D)

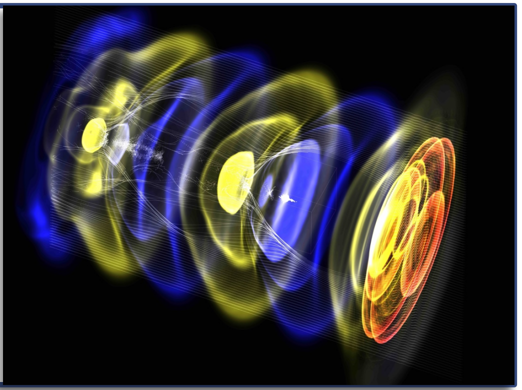
**WarpX** – open-source particle-in-cell code with advanced algorithms at Exascale

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

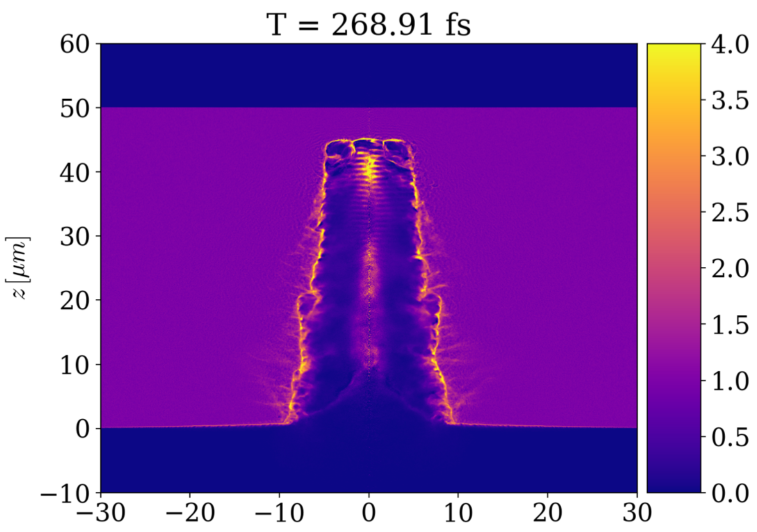
https://ecp-warpx.github.io
Vay, J-L., *et al., Nucl. Instrum. Meth. A* 909 (2018)

ECP EXASCALE COMPUTING PROJECT

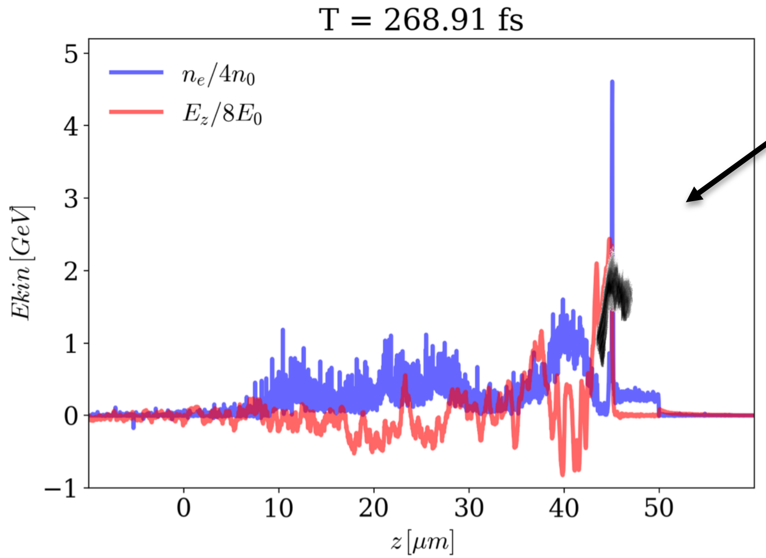
U.S. DEPARTMENT OF ENERGY | Office of Science



# We compute final proton energies of up to 2.5 GeV

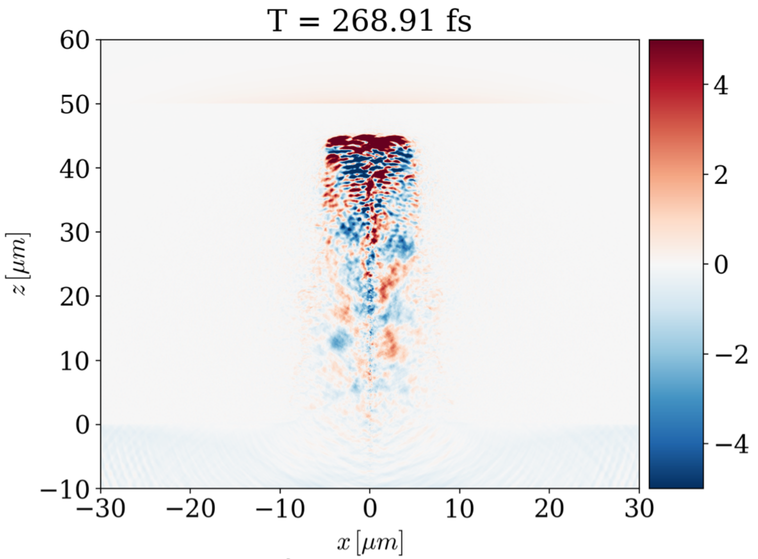



Electron density




Triangular shape of the accelerating field (red) visible in simulations

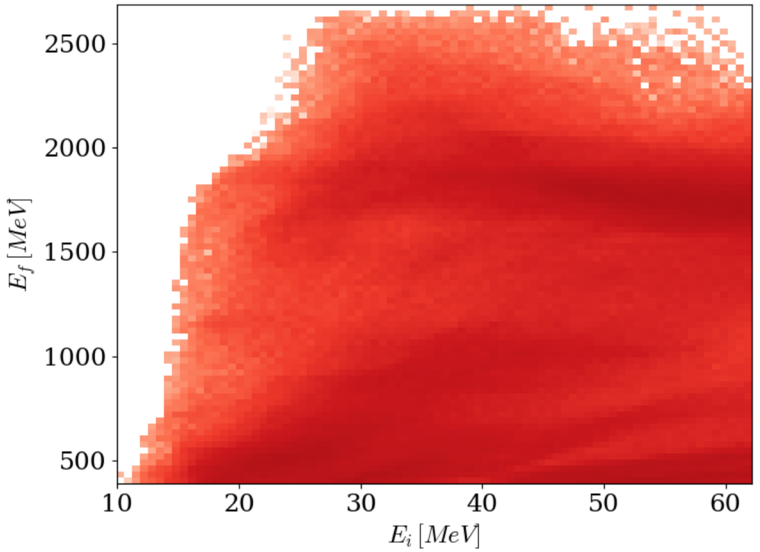
The snowplow field boosts the pre-accelerated protons energies from $30 - 60 MeV$ up to $2.5 GeV$




Accelerating field

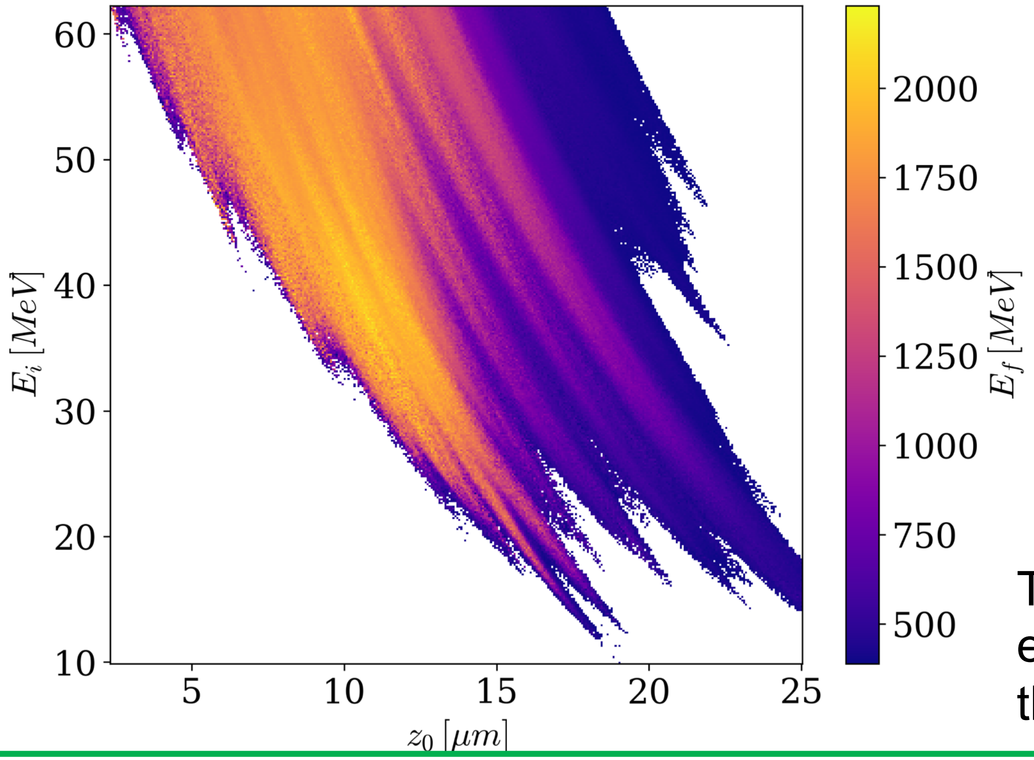
The value of the final proton energy is close to the predicted maximum for $\beta_g \simeq 0.8$ that is computed in the simulations ($E_{MAX} \sim 3GeV$)

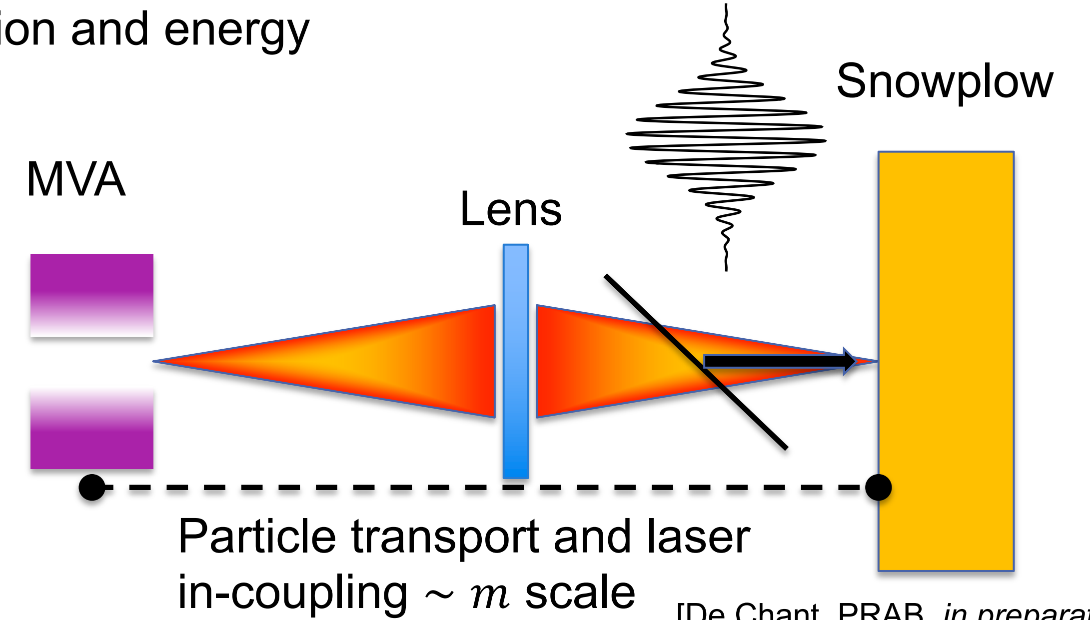
The next step is to investigate schemes to connect the source (MVA) with the snowplow



# Investigation of the transport process from the MVA to the snowplow

Final energy of the test particles in function of their initial position and energy




[De Chant, PRAB, *in preparation*]

Transport of a proton beam with $\sigma_E \sim 100\%$ results in beam elongation. We computed that $\sim pC$ proton charge generated in the MVA is trapped and post-accelerated in the snowplow stage.

It is important to study the combined system taking into account realistic parameters for combining the MVA with the snowplow. Identification of solutions to increase the trapped charge is in progress, e.g.

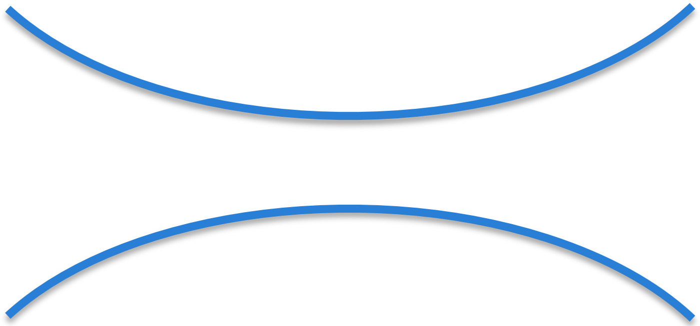
- Improvement of the source phase space
- Different options of in-coupling mechanism that reduce the distance between the source and the snowplow
- Beam chirping/compression and focusing to reduce its spread

# Three main factors limit the final energy of accelerated protons

## Laser diffraction

Limited by Rayleigh range

$$z_R = \frac{\pi w_0^2}{\lambda_0} \approx 60\mu m$$



## Laser depletion

The laser is depleted by the energy exchange with the plasma

$$L_d \propto a_0 \frac{n_c}{n_e} cT_{FWHM}$$

[Hakimi et al, POP, 2020]

For the parameters we are using in simulations (i.e. $\mathcal{E} \approx 100 - 400J$), we computed $L_d \gtrsim 100\mu m$

## Proton dephasing

The protons outrun the slow-moving snowplow field

When the group velocity $\beta_g$ of the accelerating field is $\beta_g < c$, the maximum achievable energy before dephasing is $E_{MAX} = \frac{2m_p\beta_g^2}{1-\beta_g^2}$

(i.e., analogous to a moving mirror)

[S. V. Bulanov et al, POP, 2012]

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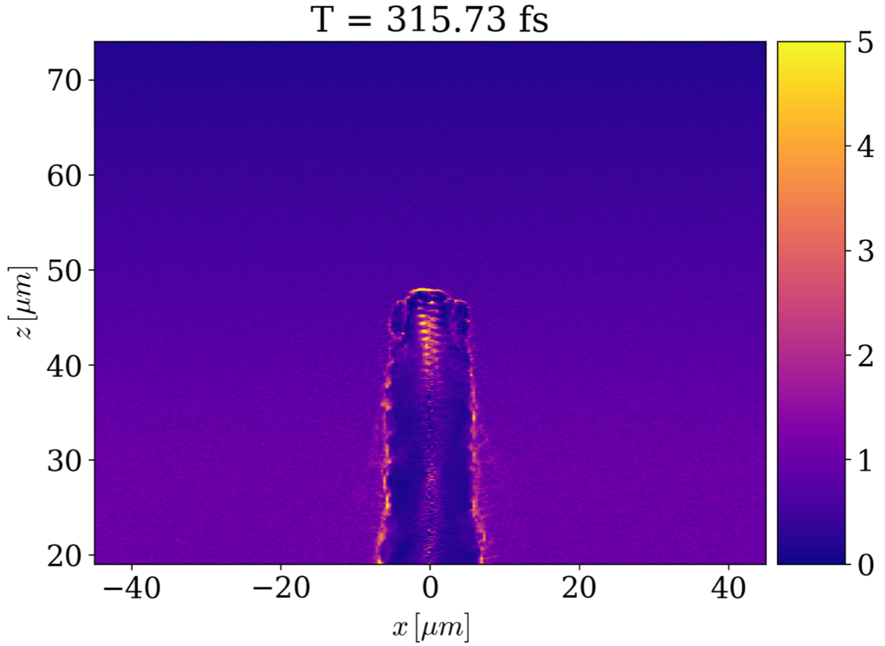
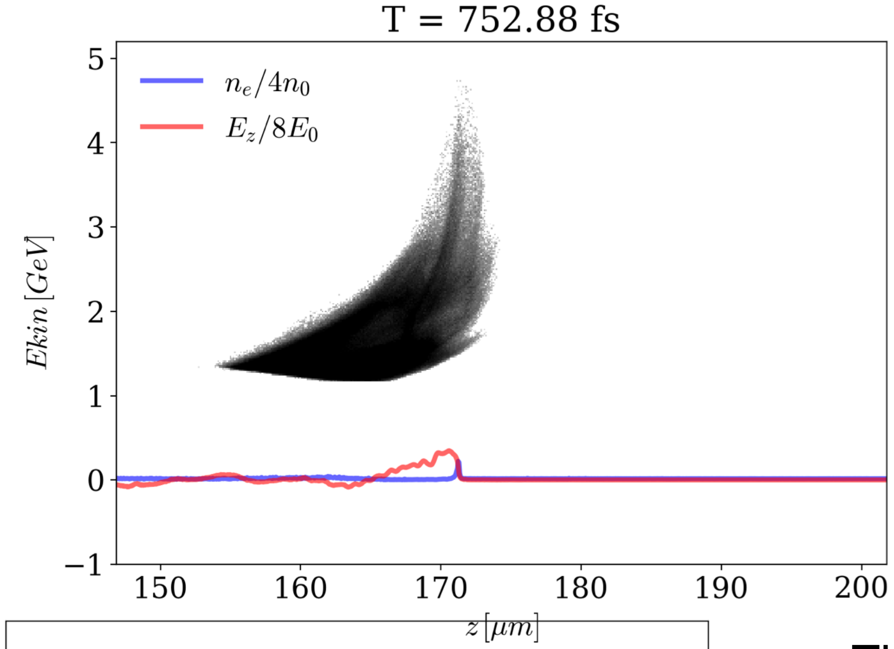
# Density tapering increases maximum proton energy

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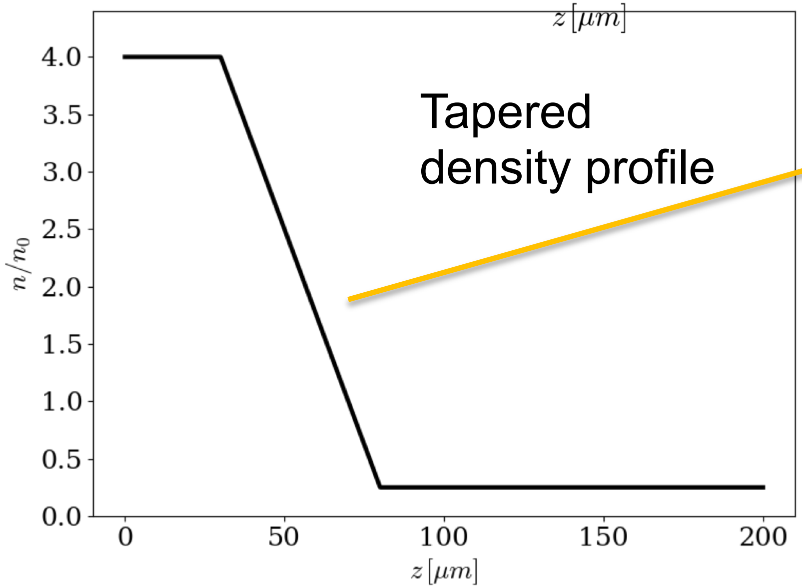
$T_{FWHM} = 35\ fs$
$\mathcal{E} \simeq 400\ J$

Circular pol.

Focused on target boundary




Tapered density profile

The group velocity of the snowplow accelerating structure increases as the density decreases

Finding an optimal density profile is work in progress as the laser evolution is very nonlinear

# Summary

- We analyzed the production of $\gtrsim GeV$ proton beams using the snowplow acceleration of pre-accelerated protons (from MVA)
- The electric field generated by a snowplow can accelerate protons up to $\sim 2-3\ GeV$ and it is limited by the proton dephasing
- Tapering the target density enables higher energy gains, limited by the laser depletion length