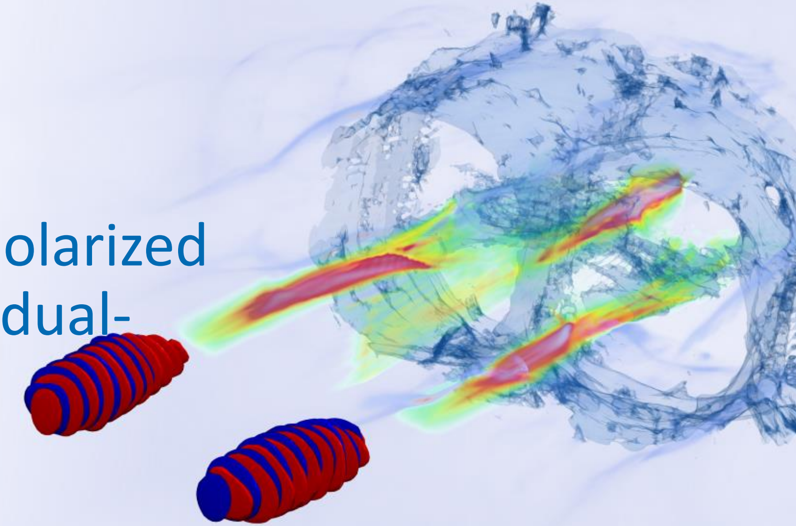
Acceleration of spin-polarized proton beams from a dual-laser pulse scheme



Lars Reichwein, Markus Büscher
and Alexander Pukhov

EuroNNAc Special Topics Workshop
22.09.2022

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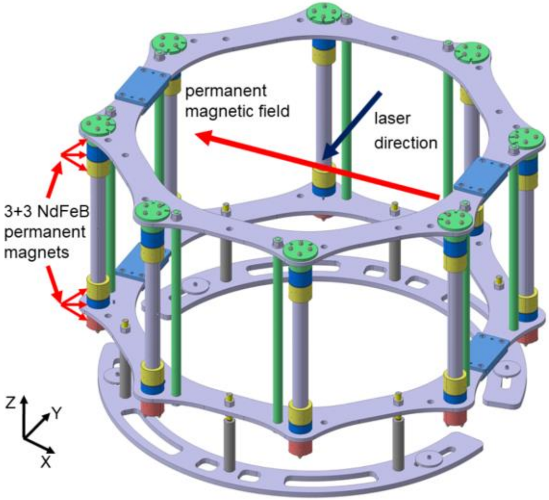
Motivation

Collaboration with FZ Jülich

- Why consider spin-polarized beams?
  - Testing the Standard Model of Particle Physics
  - Spin-polarized fusion

- **Goal:** Build a source of spin-polarized ^{3}He
- Late 2021: First measurements at GSI Darmstadt
  - Results currently being examined
  - Principal investigator: Markus Büscher
  - Further simulations: Paul Gibbon

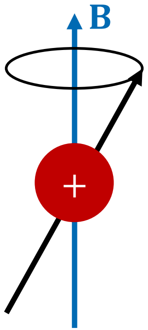
- Polarized HCl target possible as well → used here



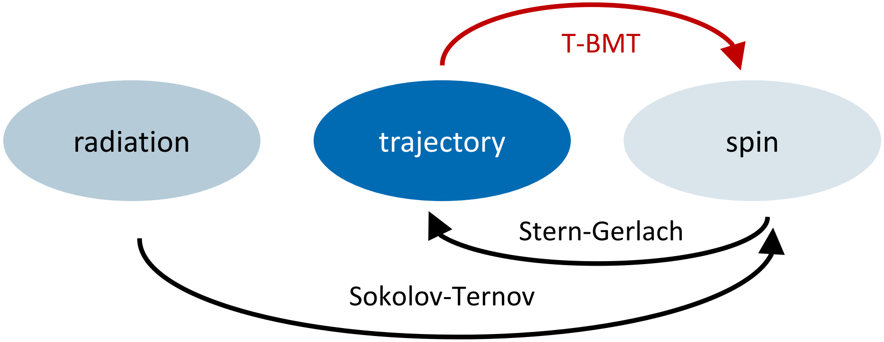
P. Fedorets et al., *Instruments* **6**(2), 18 (2022)

Interactions involving spins

Depolarization due to EM-fields



- Particle spins precess during trajectories through EM-fields
  - homogeneous fields: particle spins precess uniformly
  - inhomogeneous fields: Initially polarized beams lose polarization
- For beam collimation: significant change in el.mag. fields may lead to depolarization
  - Acceleration phase: changes in spin negligible
- Other effects like Sokolov-Ternov and Stern-Gerlach are being neglected



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Interactions involving spins

T-BMT

- Spin precession in arbitary el.mag. fields

$$\frac{\mathrm{d}\mathbf{s}}{\mathrm{d}t} = -\mathbf{\Omega} \times \mathbf{s}$$

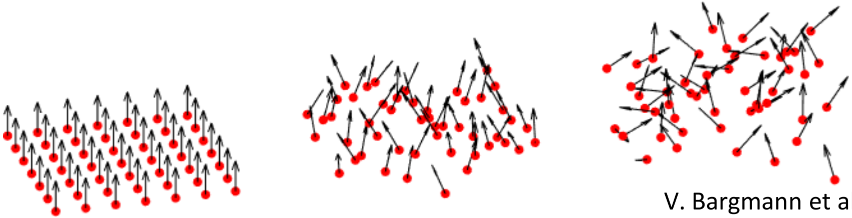
a = anomalous magnetic moment

$$a_e = \frac{\alpha}{2\pi} \approx 10^{-3}\,, \qquad a_p = \frac{a_e m_p}{m_e} \approx 1.8$$

- Rotation frequency

$$\mathbf{\Omega} = \frac{qe}{mc}\left[\Omega_B \mathbf{B} - \Omega_V \left(\frac{\mathbf{v}}{c} \cdot \mathbf{B}\right)\frac{\mathbf{v}}{c} - \Omega_E \frac{\mathbf{v}}{c} \times \mathbf{E}\right]$$

$$\Omega_B = a + \frac{1}{\gamma}, \qquad \Omega_V = \frac{a\gamma}{\gamma+1}, \qquad \Omega_E = a + \frac{1}{1+\gamma}$$

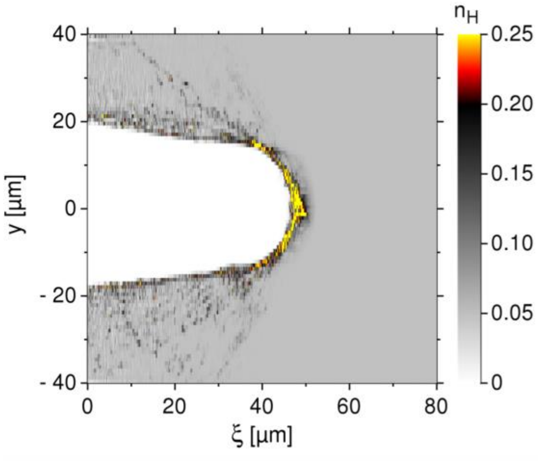


V. Bargmann et al., *Phys. Rev. Lett*. **2**, 435 (1959)
J. Thomas et al., *Phys. Rev. Accel. Beams* **23**, 064401 (2020)

Current state-of-the-art

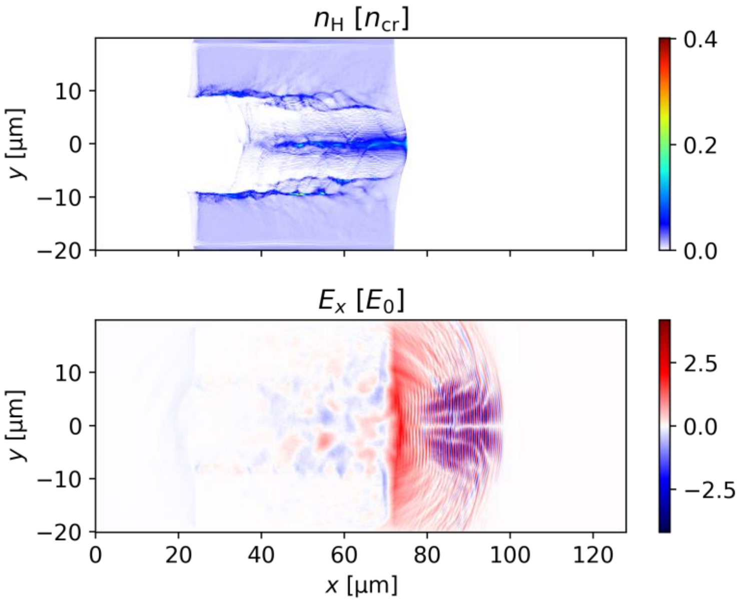
Acceleration of spin-polarized protons

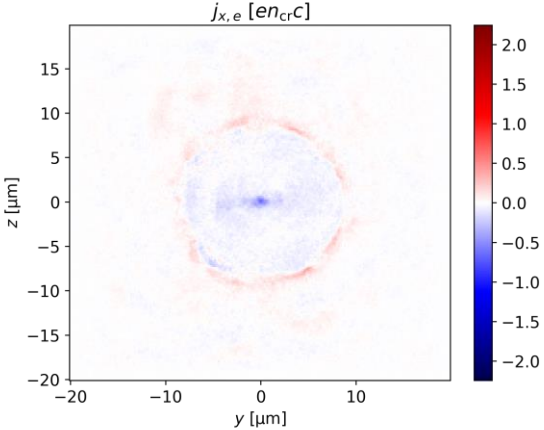
- In general: TNSA, RPA, Proton Wakefield acceleration, MVA, …
- For spin: restriction due to ability to pre-polarize targets
  - TNSA would necessitate solid-state target
  - Alternative: **Magnetic Vortex Acceleration (MVA)**



L. Reichwein et al., *PPCF* **63**, 085011 (2021)
A. Hützen et al., *J. Phys.: Conf. Ser.* **1596,** 012013 (2020)

Magnetic Vortex Acceleration (MVA)





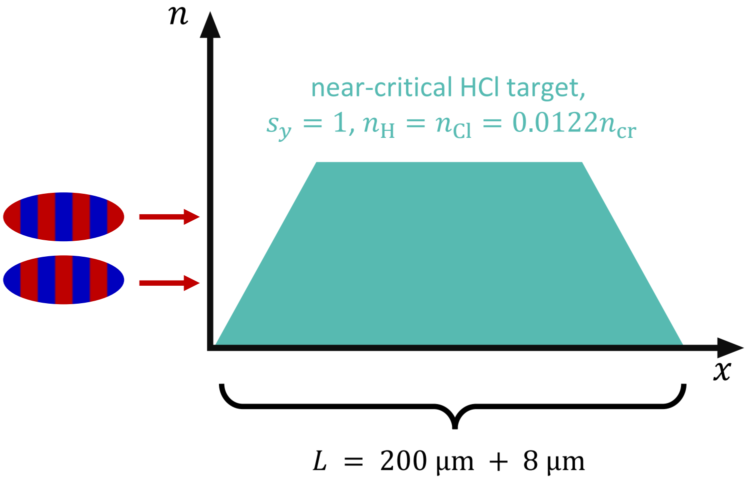
L. Reichwein et al., *PRAB* **25**, 081001 (2022)

Dual-pulse setup for proton acceleration

Configuration

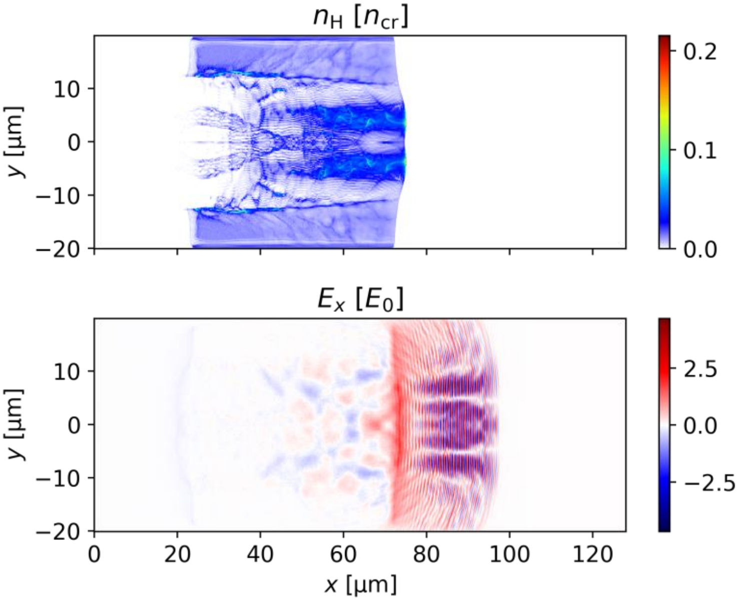
- „Dipole“ laser: two parallel propagating laser pulses
  - $\lambda_L = 800\ \mathrm{nm}$
  - $a_0 = 25 - 100$
  - $\tau = 26.7\ \mathrm{fs}$
  - $w_0 = 4\ \mu\mathrm{m}$

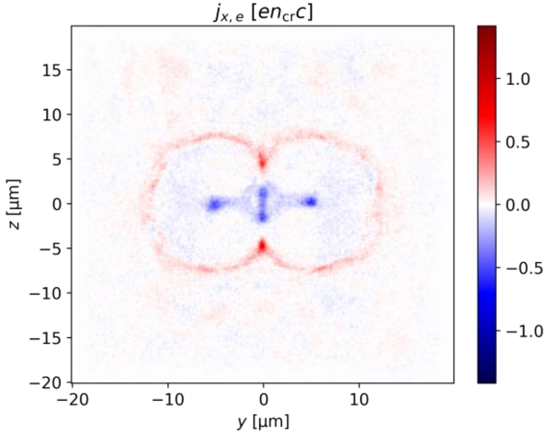
- Spatial separation $\Delta y = 8\ \mu\mathrm{m}$
- Phase difference of π



L. Reichwein et al., *PRAB* **25**, 081001 (2022)

Dual-pulse setup for proton acceleration

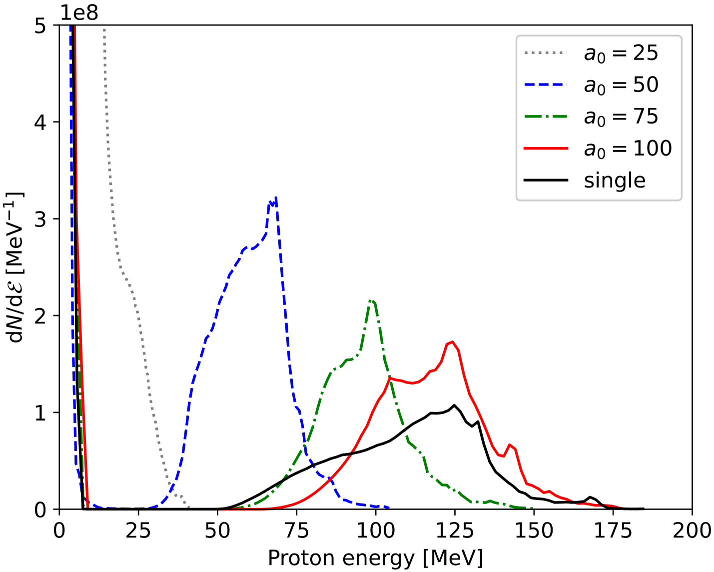




L. Reichwein et al., *PRAB* **25**, 081001 (2022)

Results

Energy spectrum (protons with < 2° momentum spread)



a_0	E_{peak} [MeV]	E_{max} [MeV]	Q_{FWHM} [nC]
50 (d)	68.5	107.8	1.07
75 (d)	98.3	156.1	0.61
100 (d)	124.3	181.8	0.76
141 (s)	124.8	186.3	0.61

L. Reichwein et al., *PRAB* **25**, 081001 (2022)

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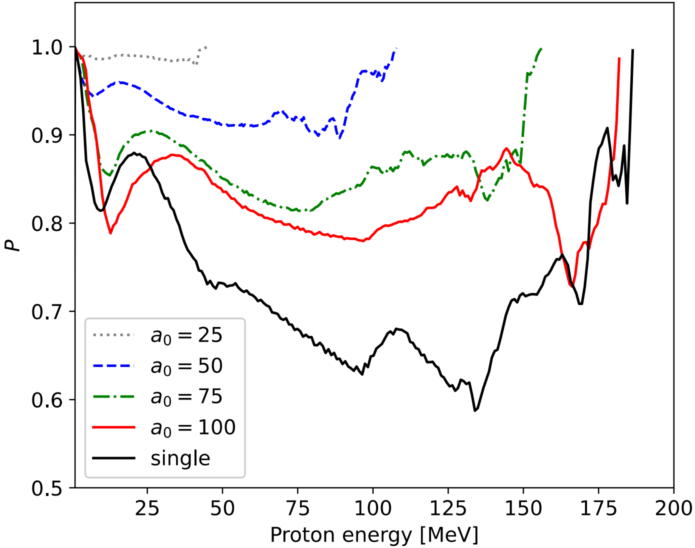
Results

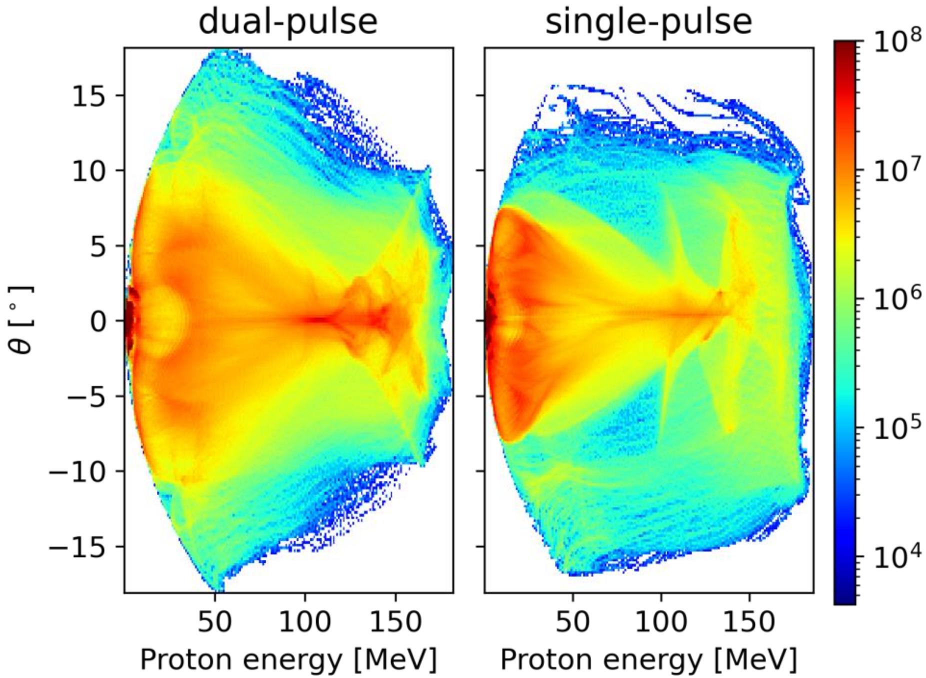
Polarization



a_0	E_{peak} [MeV]	E_{max} [MeV]	Q_{FWHM} [nC]	P_{FWHM} [%]
50 (d)	68.5	107.8	1.07	93
75 (d)	98.3	156.1	0.61	84
100 (d)	124.3	181.8	0.76	77
141 (s)	124.8	186.3	0.61	64

L. Reichwein et al., *PRAB* **25**, 081001 (2022)

Angular spectrum



L. Reichwein et al., *PRAB* **25**, 081001 (2022)

Summary/Outlook

- Dual-pulse setup allows for high-energy protons
- Higher polarization compared to typical MVA
- No asymmetry in angular spectrum

- What can be looked at in the future?
  - Influence of QED effects for higher laser intensities
  - Use of initially unpolarized targets [like Nie *et al., PRL* **127**, 269901 (2021) for electrons]

- State-of-the-art: M. Büscher et al., *High Power Laser Sci* **8**, e36 (2020)

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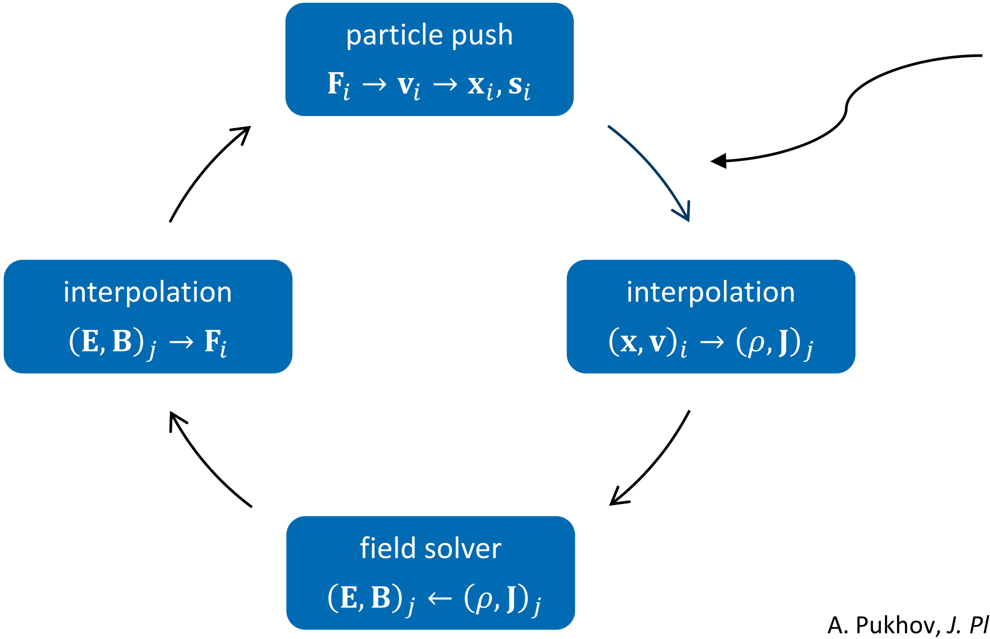
Universität Düsseldorf

Backup Slides

Interactions involving spins

Particle-in-cell simulations



particle push

$\mathbf{F}_i \rightarrow \mathbf{v}_i \rightarrow \mathbf{x}_i, \mathbf{s}_i$

interpolation

$(\mathbf{E}, \mathbf{B})_j \rightarrow \mathbf{F}_i$

interpolation

$(\mathbf{x}, \mathbf{v})_i \rightarrow (\rho, \mathbf{J})_j$

field solver

$(\mathbf{E}, \mathbf{B})_j \leftarrow (\rho, \mathbf{J})_j$

Spin precession
described by T-BMT

$$\frac{\mathrm{d}\mathbf{s}_i}{\mathrm{d}t} = -\boldsymbol{\Omega} \times \mathbf{s}_i$$

A. Pukhov, *J. Plasma Phys.* **61**(3), 425-433 (1999)
A. Pukhov, *CERN Yellow Reports* **1,** 181-206 (2016)

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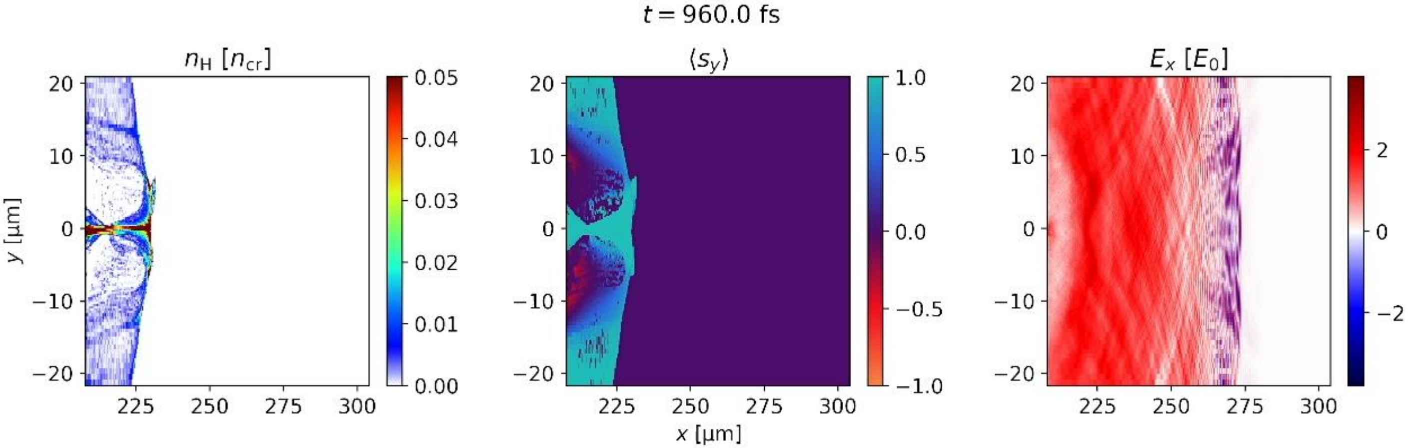
Dual-pulse setup for proton acceleration

PIC simulation results (Movie)



L. Reichwein et al., *PRAB* **25**, 081001 (2022)