FLASHFORWARD INTO THE FUTURE

Challenges and Prospects for Plasma-Wave Acceleration

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Accelerator Research and Development, Matter and Technologies
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> …many DESY engineering & technical support groups
active collaboration partners

Helmholtz

Universities

National labs

Networks
Accelerators are at the heart of high-energy photon sources and particle colliders.

CUTTING-EDGE, HIGH-END SLOW-MOTION-CAMERAS AND MICROSCOPES TO STUDY THE STRUCTURE OF MATTER.

Particle colliders
investigation of the fundamental forces and constituents of matter.
Accelerators are at the heart of high-energy photon sources and particle colliders

CUTTING-EDGE, HIGH-END SLOW-MOTION-CAMERAS AND MICROSCOPES TO STUDY THE STRUCTURE OF MATTER

Synchrotron photon sources, e.g. Free-Electron Lasers (FELs)
investigation of processes on atomic and molecular scales

Particle colliders
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CUTTING-EDGE, HIGH-END SLOW-MOTION-CAMERAS AND MICROSCOPES TO STUDY THE STRUCTURE OF MATTER

Synchrotron photon sources, e.g. Free-Electron Lasers (FELs)
investigation of processes on atomic and molecular scales

Particle colliders
investigation of the fundamental forces and constituents of matter

Applications beyond matter
- medical accelerators (e.g. cancer therapy, imaging)
- material processing (e.g. food sterilization, welding)
- accelerator-driven reactors
- cargo scanning (e.g. for nuclear contraband)
BELLA
4.3 GeV
→ 0.09 m

PETRA III
6 GeV
→ 2300 m

FLASH
1.25 GeV
→ 315 m

European X-FEL
17.5 GeV
→ 3400 m

BELLA
4.3 GeV → 0.09 m


CLEAR
kT/m plasma lens → 0.015 m

FLASHForward
2.5 GeV (from simulation) → 0.03 to 0.30 m
Plasma wakefield acceleration in a nutshell

Driver

Plasma target

~cm scale length

Witness

Laser-pulse driven
“Laser wakefield acceleration”
LWFA

Particle-beam driven
“Plasma wakefield acceleration”
PWFA

Hydrogen plasma:
a soup of electrons and protons
Plasma wakefield acceleration in a nutshell

Laser-pulse driven
“Laser wakefield acceleration”
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Particle-beam driven
“Plasma wakefield acceleration”
PWFA

Protons to electron mass ~1836, heavier particles hardly move
Plasma wakefield acceleration in a nutshell

Driver acts as electron “snow plow”, static protons pull back electrons
Plasma wakefield acceleration in a nutshell

**Driver**
- Laser-pulse driven
  - “Laser wakefield acceleration” (LWFA)
- Particle-beam driven
  - “Plasma wakefield acceleration” (PWFA)

**Plasma target**

**Witness**
- Driver acts as electron “snow plow”, static protons pull back electrons
Plasma wakefield acceleration in a nutshell

Driver acts as electron “snow plow”, static protons pull back electrons

Particle-beam driven
“Plasma wakefield acceleration”
PWFA

FSU Jena, Gruppe M. Kaluza

$\begin{align*}
\text{n}_e &= 1.7 \times 10^{19} \text{ cm}^{-3}, \\
\lambda_{\text{plasma}} &= 9 \mu\text{m}
\end{align*}$

M. Schnell et al., Nat. Comm. 4, 2421 (2013)
Plasma wakefield acceleration in a nutshell

**Driver**
- Laser-pulse driven
  - "Laser wakefield acceleration" (LWFA)
- Particle-beam driven
  - "Plasma wakefield acceleration" (PWFA)

**Witness**
- GeV energy gain over cm
- ~fs duration
- ~kA current
- ~µm emittance

**Size of structure**
\[ \lambda_p \approx \frac{2\pi c}{\omega_p} \approx (33 \text{ km}) \sqrt{n_e^{-1} \text{ cm}^{-3}} \]
- Typically \( \lambda_p \approx 100 \mu m \) (for \( n_e \approx 10^{17} \text{ cm}^{-3} \))

**Electric field strength**
\[ E \approx \frac{mc\omega_p}{e} \approx (96 \text{ V/m}) \sqrt{n_e \text{ cm}^{-3}} \]
- Typically \( E \approx 33 \text{ GV/m} \) (for \( n_e \approx 10^{17} \text{ cm}^{-3} \))

- Bunch duration: fs
  - A. Buck et al., Nature Physics 7, 543 (2011)

- GeV energy gain over cm
FLASH
1.25 GeV
→ 315 m

European X-FEL
17.5 GeV
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6 GeV
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FLASH
1.25 GeV
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PWFA research
+ LWFA for medical imaging

Image: Landsat/Copernicus

Google Earth
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MEDICAL IMAGING PROTOTYPING

laser-wakefield accelerator application

Plasma accelerator (2 mm long)

> driven by 25 TW Ti:sapphire laser
> *typical:* ionization injection at 1 Hz (up to 10 Hz):
  ~1 mrad divergence, ~1 mrad pointing stability from source,
  ~1 µm norm. emittance, 48 ± 5 pC of charge, energy up to 160 MeV
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**MEDICAL IMAGING PROTOTYPING**

**laser-wakefield accelerator application**

**Plasma accelerator (2 mm long)**
- driven by 25 TW Ti:sapphire laser
- *typical:* ionization injection at 1 Hz (up to 10 Hz):
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**Active plasma lens (15 mm long)**
- driven by 20 kV discharge
- radially symmetric, kT/m focussing optic


~0.2 m
Beam extraction from plasma with conservation of transverse normalized emittance

- beams at plasma exit:
  - ~% level energy spread
  - ≤ mm beta function, ~mrad divergence

leads to transverse emittance growth in free drift


\[ \varepsilon_n^2 \cong \langle \gamma \rangle^2 \cdot (\sigma_E^2 \sigma_x^4 \sigma_z^2 + \varepsilon^2) \]

Beam extraction from plasma with conservation of transverse normalized emittance


> beams at plasma exit:
  - ~% level energy spread
  - ≤ mm beta function, ~mrad divergence

> leads to transverse emittance growth in free drift

> Plasma-to-vacuum transition ≫ β for emittance preservation
> Strong quadrupoles for beam capturing required
  Example: 1 GeV beam with 100 T/m quads fully captured only ~1 m behind plasma → emittance growth factor > 2
Prototype R&D: aberration-free active plasma lenses

First measurements reveal non-linear focussing fields

- Strong focussing optics are desirable for emittance-preserving beam capturing after release into vacuum
- Active plasma lenses are a promising technology providing up to 3 kT/m symmetric fields

\[ F = I \times B, \text{ tunable and symmetric focussing force for } e\text{-beam} \]

Field measurements reveal non-linearity consistent with measured emittance growth

Likely cause: temperature gradients

Prototype R&D: aberration-free active plasma lenses

EMITTANCE PRESERVATION REALIZED WITH HEAVY GAS SPECIES

- Idea: utilize APL before temperature equilibration can take place
- Substitute Hydrogen/Helium with Argon to extend timescale $\propto m_{\text{ion}}$
- Experiment at CLEAR, CERN: 216 MeV, 50 $\mu$m rms size, 3 $\mu$m trans. norm. emittance, 410 A current at 70 ns
- Argon: emittance conservation demonstrated
  Helium: emittance not conserved

Technology attractive for
- beam capturing from plasma
- positron capturing
- adiabatic final focussing (Oide limit)

Scanning X-ray fluorescence imaging (XFI)

- imaging of gold-nanoclusters bound to anti-bodies (bound to tumors, …)
- fluorescence signal excited by ~100 keV X-rays from Thomson scattering off LWFA electrons
- 2-year goal: method proof-of-principle on isolated prostate tumor cells (end of 2019)
- distant goal: pharmacokinetics and high-resolution detection of tumors in-vivo

Supported by DESY Strategy Fund
What about high average power applications with LWFAs?

**EXAMPLE: PARTICLE COLLIDER → BACK-OF-THE-ENVELOPE POWER ESTIMATES REVEAL MAIN CHALLENGE**

| Required power per particle beam $P_b \approx 5 \text{ MW}$ | confer C.B. Schroeder *et al.*, Phys. Rev. STAB 13, 101301 (2010) |
| Maximum power from the grid $P_{AC} \approx 200 \text{ MW}$ | confer B. Shadwick *et al.*, Phys. Plasmas 16, 056704 (2009) |
| → Need 5% wallplug efficiency | from simulations |
| → Efficiency laser to plasma wave $\sim 50\%$ | |
| → Efficiency plasma wave to beam $\sim 30\%$ | |
| → Expected laser-to-beam efficiency $15\%$ | |
| → Requires wallplug-to-laser efficiency $33\%$ | |

With 10 GeV LWFA stage $\times 50$ and total energy per beam $\sim 300 \text{ J}$

| → 6 J energy gain per module | |
| → 40 J laser energy per module at $\sim 17 \text{ kHz}$ repetition rate | |
| → $680 \text{ kW}$ average laser power required | |

Modern 1 PW LWFA lasers: $\ll 1\%$ wallplug efficiency, 1 Hz repetition rate, $\sim 100 \text{ W}$ average power

FLASH
1.25 GeV → 315 m

European X-FEL
17.5 GeV → 3400 m

PETRA III
6 GeV → 2300 m

PWFA research + LWFA for medical imaging
**FLASH drives free-electron laser and accelerator research**

Superconducting, high-average power system feeds multiple beam lines simultaneously

<table>
<thead>
<tr>
<th>5 MeV</th>
<th>150 MeV</th>
<th>450 MeV</th>
<th>1250 MeV</th>
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<tbody>
<tr>
<td>ACC1</td>
<td>BC2</td>
<td>ACC23</td>
<td>BC3</td>
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<td>ACC39</td>
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<td>ACC45</td>
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<tr>
<td>ACC67</td>
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<td>ACC67</td>
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</tbody>
</table>

**Photo cathode**

ACC → SCRF modules

BC → Bunch compressors

FLASH is an FEL user facility

- 10% of beam time (750 h / year) dedicated to accelerator research

FLASHForward is a beam line for PWFA research

Both share the same superconducting accelerator based on ILC/XFEL technology. Typical electron beam parameters:

- \( \leq 1.25 \text{ GeV energy with a few 100 pC at } \sim 100 \text{ fs rms bunch duration} \)
- \( \sim 2 \mu m \text{ trans. norm. emittance} \)
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FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

- a next-generation experiment for beam-driven plasma wakefield accelerator research
- unique FLASH facility features for PWFA
  - differentially pumped, windowless plasma source
  - 3rd harmonic cavity for phase-space linearization
    → shaping of beam current profile
  - 2019: X-band deflector of 1 fs resolution post-plasma
    (collaboration with FLASH 2, SINBAD, CERN & PSI)
  - future: up to 800 bunches (~MHz spacing)
    at 10 Hz macro-pulse rate, few 10 kW average power

→ A. Aschikhin et al., NIM A 806, 175 (2016)
FLASHFoward
Future-oriented wakefield accelerator research and development

- Beamline commissioning August 30th, 2017 - June 30th, 2018
- Experimentation started after July 15th, 2018

Laser transport beamline completed summer 2017

First beam in FF - August 31, 2017

LYSO screen station

Central interaction area

Final focusing section

Differential pumping

Dispersive section

Electron beamline enabling first experiments, summer 2018
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FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

electron beamline enabling first experiments, summer 2018

plasma source
30 mm long (up to 300 mm possible)
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FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

> first PWFA beam-plasma interaction on June 19th, 2018
> commissioning successful and quasi-finished June 30th, 2018
> installation ready for first experiments after July 15th, 2018

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30 mm long (up to 300 mm possible)
FLASHFORWARD

FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

> first PWFA beam-plasma interaction on June 19th, 2018
> commissioning successful and quasi-finished June 30th, 2018
> installation ready for first experiments after July 15th, 2018

(12.3 ± 1.7) GV/m wakefield generated in 30 mm plasma cell
→ plasma cell scale length ~100 mm for GeV energy gain confirmed

12.7% total energy loss to plasma wakefield

plasma source
30 mm long (up to 300 mm possible)
Main FF scientific goals

> **X-1 Plasma cathode**: high-brightness beam generation (→ photon science)
  > 1.25 GeV energy, trans. norm. emittance ~100 nm, current \( \geq 1 \) kA, ~fs bunch duration

> **X-2 Plasma booster**: wakefield module for post acceleration (→ staging, high-energy physics)
  energy doubling, energy spread & emittance preservation, drive depletion (> 10% efficiency)

> **X-100 Investigate plasma-accelerated beams for FEL gain** (PHASE II, 2020+)

### ADVANCED DIAGNOSTICS AND PROTOTYPES

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<tr>
<th>P-1</th>
<th>TR Spectroscopy</th>
<th>P-5</th>
<th>( \perp ) Beam Probe</th>
<th>P-9</th>
<th>P-10</th>
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<tr>
<td></td>
<td>PI: B. Schmidt (DESY)</td>
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<td>PI: P. Niknejadi (DESY)</td>
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<td>PI: A. Knetsch (DESY)</td>
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<td>P-3</td>
<td>Betatron Radiation</td>
<td>P-6</td>
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<td>PI: S.P.D. Mangles (ICL)</td>
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<td>PI: S. Wesch (DESY)</td>
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<td>PI: S. Bohlen (DESY)</td>
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<tr>
<td>P-4</td>
<td>( \perp ) Laser Probe</td>
<td>P-8</td>
<td>Active Plasma Lens</td>
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<tr>
<td></td>
<td>PI: M. Kaluza (U Jena)</td>
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<td>PI: L. Schaper (DESY)</td>
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### CORE EXPERIMENTS

| X-1 | Plasma Cathode
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<tbody>
<tr>
<td></td>
<td>PI: A. Knetsch (DESY)</td>
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</tbody>
</table>
| X-2 | Plasma Booster
|     | PI: V. Libov (U Hamburg) |
| X-10| Transformer Ratio ↑
|     | PI: V. Libov (U Hamburg) |
| X-11| Hosing Studies
|     | PI: S. Wesch (DESY) |
| X-12| MHz PWFA
|     | PI: R. D’Arcy (DESY) |
| X-16| Beam (De-)chirping
|     | PI: R. D’Arcy (DESY) |
| X-19| Ion Motion Studies
|     | PI: t.b.d. |
| X-23| Ionization Studies
|     | PI: t.b.d. |
| X-100| FEL Gain
|      | PI: t.b.d. |
First study: a tunable plasma-based energy dechirper

NOVEL TECHNOLOGY FOR REMOVING LONGITUDINAL ENERGY CORRELATION BY PLASMA WAKEFIELDS

- Beams from plasma wakefield accelerators may feature large chirps of order 100 MeV/mm
- Dechirping structures demonstrated up to 18 MeV/m/mm — insufficient (e.g. K.L.F. Bane, G. Stupakov, NIM A 690, 106 (2012) or S. Antipov et al., Phys. Rev. Lett. 112, 114801 (2014))
- The idea: utilize plasma wakefield to remove chirp
  - slice-energy change given by $\Delta \gamma(\zeta) = -k_p L_p E_z(\zeta)/E_0$

- experimental idea

Dechirping magnitude depends on
- bunch profile
- plasma length
- plasma density

Dechirping magnitude depends on
- bunch profile
- plasma length
- plasma density
First study: a tunable plasma-based energy dechirper

Proof-of-principle experiment to remove chirp of FLASH beam in plasma cell

- Reduction of energy spread from 1.3% to 0.3% FWHM
- Experimental demonstration of 1.8 GeV/m/mm dechirping strength
- May dramatically improve applicability of PWFA beams

X-13 Beam (De-)chirping
  PI: R. D’Arcy (DESY)

PIC simulations fit very well
- Plasma process had no measurable impact on beam stability

→ R. D’Arcy et al., submitted (2018)
Core study: a plasma-based energy booster module

Driver/witness-pair creation in dispersive section by variable mask

Beam scraper for driver/witness-pair creation

Full start-to-end simulation

Current (A) vs. z (mm)

Electron beam

Metallic slab

Side blocks

3 mm

100 µm

Cu + W alloy

Variable bunch separation

Driver

Witness

idea follows P. Muggli et al., PRSTAB 13, 052803 (2010)

X-2 Plasma Booster

PI: V. Libov (U Hamburg)

Installed in July 2018

FLASH 2

Flash Forward

B EAM SCRAPER FOR DRIVER/WITNESS-PAIR CREATION

Current (A)
Core study: a plasma-based energy booster module

CURRENT-PROFILE SHAPING FOR TRANSFORMER RATIO MAXIMIZATION

BEAM SCRAPPER FOR DRIVER/WITNESS-PAIR CREATION

Driver
Witness
variable bunch separation

FLASH2
FLASH

Full start-to-end simulation

Core study: a plasma-based energy booster module

CURRENT-PROFILE SHAPING FOR TRANSFORMER RATIO MAXIMIZATION

DRIVE BEAM SHAPING FOR TRANSFORMER RATIO MAXIMIZATION

- Transformer ratio TR ≤ 2 for symmetric drive bunch
- Current shaping for driver can overcome this, triangular beams → uniform longitudinal fields and energy loss

TR = \( \frac{E_{\text{acc}}}{E_{\text{dec}}} \)

- First detection of increased TR in plasma at PITZ, DESY Zeuthen
- TR = 4.6 ± 0.4


X-2 Plasma Booster
- PI: V. Libov (U Hamburg)
Core study: a plasma-based energy booster module

Current-profile shaping for energy spread and emittance preservation

Beam scraper for driver/witness-pair creation

- 3.9 GHz cavity and compressors for beam shaping at FLASH
- Shaped current profiles allow for uniform fields at driver and witness locations

Beam shaping for beam loading/transformer ratio control

- Triangular witness profile for energy spread conservation

Full start-to-end simulation

Current (A)

X-2 Plasma Booster
- PI: V. Libov (U Hamburg)
Core study: a plasma-based energy booster module

Current-profile shaping for energy spread and emittance preservation

Beam scraper for driver/witness-pair creation

Full start-to-end simulation

Emittance and energy spread largely conserved in simulations

Initial norm. emittance 2.0 µm, energy spread 0.2%, energy 1.0 GeV

X-2 Plasma Booster
  PI: V. Libov (U Hamburg)
Core study: a plasma-based energy booster module

EXPERIMENTAL DRIVER/WITNESS CREATION

BEAM SCRAPER FOR DRIVER/WITNESS-PAIR CREATION

Scraper commissioning

- Long. phase space pre-scraper from LOLA transverse deflector
- Measured post-scraper spectrometer data consistent with simulations
- Direct proof of double-bunch generation with transverse deflector in 2019

Full start-to-end simulation

X-2 Plasma Booster

- PI: V. Libov (U Hamburg)
**Future study:** hosing growth rates and mitigation

**Start-to-end simulations show excitation of the hosing instability**

- Asymmetries in charge distribution and momentum expected, seed the hosing instability
- Asymmetries caused by coupler kicks and CSR in bends

*Simulation of charge distribution before plasma*

*Formation of slice-centroid offsets in high-current bunches*

- Emission of synchrotron radiation in dispersive element → causes energy loss → dispersion not closed → kick/offset w.r.t. reference orbit
- Energy loss/kick dependent on slice current → non-uniform along beam
- Emitted radiation acts back on beam
**Future study:** hosing growth rates and mitigation

**START-TO-END SIMULATIONS SHOW EXCITATION OF THE HOSING INSTABILITY**

- Asymmetries in charge distribution and momentum expected, seed the hosing instability
- Asymmetries caused by coupler kicks and CSR in bends
- Full start-to-end simulations incl. CSR predict hosing modes can be (easily) excited
- Measurement of growth rates & hosing saturation vs. beam parameters one of next steps at FLASHForward

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**Simulated charge distribution before plasma**

- **y (mm)**
- **z (mm)**

**Witness**  **Driver**

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X-11  Hosing Studies  
- PI: S. Wesch (DESY)
**Future study:** hosing growth rates and mitigation

Start-to-end simulations show excitation of the hosing instability - Experiments not yet

Full start-to-end simulations incl. CSR predict hosing modes can be (easily) excited

Measurement of growth rates & hosing saturation vs. beam parameters one of next steps at FLASHForward

No sign of hosing so far in experiments

Suppressed owing to large focal size? (current diagnostic resolution limited at ~20µm…)

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Hosing mitigation


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**Hosing Studies**

- PI: S. Wesch (DESY)
Plasma-based accelerator science at **FLASHFORWARD**

**SMALL IS BEAUTIFUL (AND USEFUL*)**

- Plasma wakefield acceleration is an intriguing technology to radically miniaturize particle accelerators
- First applications with laser drivers in photon science and medical imaging are within reach
- High-average power applications are incompatible with current laser technology, will require particle beam drivers (for the foreseeable future)
- **FLASHFORWARD** is a unique, next-generation experiment toward high-brightness, high-quality, high-average power plasma accelerators
- Experiments have started this summer. Exciting times are ahead!

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**Beam-driven wakefield acceleration**

GeV energy booster, high-brightness beams

**Aberration-free active plasma lens**

sym. kT/m focussing