FLASHFORWARD - STATUS AND PLANS
Future-Oriented Wakefield-Accelerator Research and Development at FLASH

Richard D’Arcy

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Accelerator Research and Development, Matter and Technologies
Helmholtz Association of German Research Centres, Berlin, Germany
Core FLASHForward team

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- Lars Goldberg
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- Jan-Hendrik Röckemann
- Sarah Schröder
- Jan-Patrick Schwinkendorf
- Bridget Sheeran
- Gabriele Tauscher
- Paul Winkler

**Postdocs**
- Alexander Knetsch
- Vladyslav Libov
- Alberto Martinez de la Ossa
- Timon Mehrling
- Zeng Ming
- Pardis Niknejadi
- Kristjan Pöder
- Lucas Schaper
- Stephan Wesch

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- Sven Karstensen
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- Frank Marutzky
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**Students**
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- Martin Quast

**Desy engineering & technical support groups**

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**Collaboration partners**
- Universität Hamburg, Germany
- John Adams Institute, UK
- Lawrence Berkeley National Laboratory, US
- Stanford Linear Accelerator Center, US
- James Cook University, Australia
- Max Planck Institute for Physics, Bavaria
- CERN, Switzerland
- Laboratori Nazionali di Frascati, Italy
- University of California Los Angeles, US
- Instituto Superior Técnico Lisboa, Portugal
- University of Oslo, Norway
- Friedrich-Schiller-Universität Jena, Germany
- Heinrich-Heine-Universität Düsseldorf, Germany
FLASH drives free-electron laser and accelerator research
SUPERCONDUCTING SYSTEM FEEDS MULTIPLE BEAM LINES SIMULTANEOUSLY

FLASH is an FEL user facility
FLASHForward is a plasma wakefield accelerator experiment → A. Aschikhin et al., NIM A 806, 175 (2016)

Shares the same superconducting accelerator front-end. Typical electron beam parameters:
- \(\lesssim 1.25\) GeV energy with a few 100 pC at \(~100\) fs rms bunch duration
- \(~2 \mu m\) trans. norm. emittance
- up to 800 bunches (\(\lesssim \) MHz spacing) at 10 Hz macro-pulse repetition rate, a few 10 kW average beam power
FLASHFORWARD

ACC1  BC2  ACC23  BC3  ACC45  ACC67

Photo cathode
FLASHFORWARD

A NEXT-GENERATION EXPERIMENT FOR BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATION

- planned beamline completion in January 2018 (as depicted): ready for plasma experiments
- 60 hours of commissioning in parallel to FLASH1 operation performed (started Aug 30 2017)
- 72 hours of dedicated commissioning completed in Nov 2017

First beam in FF - August 31, 2017

LYSO screen station
follows a staggered installation plan

**PROJECT PHASE I: PLASMA WAKEFIELD BEAMLINES AND DIAGNOSTICS — PHASE II: UNDULATOR INTEGRATION**

- installation proceeds in FLASH shutdowns, typically January and July of each year
- tremendous support of FLASH coordination
Experimental programme in preparation

SEPARETED INTO CORE EXPERIMENTAL STUDIES AND PROTOTYPING

**CORE EXPERIMENTS**

| X-1 Plasma Cathode | PI: A. Knetsch (DESY) |

### Main scientific goals

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

→ A.Martinez de la Ossa *et al.*, PRAB 20, 091301 (2017)

### Technical challenges

- Tailored, windowless plasma sources:
  - controlled density-downramp injection, hosing mitigation, controlled witness release

**Example profile**

- Laser or HV ionised, up to 30 cm long

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

**Technical challenges**

- Tailored, windowless plasma sources:
  - Hosing mitigation, controlled witness matching, controlled witness release

- **Two-bunch generation**:
  - Tunable separation of ~100 µm, shaping for beam loading and transformer ratio control
Experimental programme in preparation

**SEPARATED INTO CORE EXPERIMENTAL STUDIES AND PROTOTYPING**

### Core Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
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<tbody>
<tr>
<td>X-1</td>
<td>Plasma Cathode&lt;br&gt;PI: A. Knetsch (DESY)</td>
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<tr>
<td>X-2</td>
<td>Plasma Booster&lt;br&gt;PI: V. Libov (U Hamburg)</td>
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<td>X-10</td>
<td>Transformer Ratio&lt;br&gt;PI: V. Libov (U Hamburg)</td>
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<td>X-11</td>
<td>Hosing Studies&lt;br&gt;PI: S. Wesch (DESY)</td>
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<td>X-12</td>
<td>MHz PWFA&lt;br&gt;PI: R. D’Arcy (DESY)</td>
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<td>X-13</td>
<td>Beam (De-)chirping&lt;br&gt;PI: R. D’Arcy (DESY)</td>
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<td>X-14</td>
<td>Ion Motion Studies&lt;br&gt;PI: t.b.d.</td>
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<tr>
<td>X-100</td>
<td>FEL Gain&lt;br&gt;PI: t.b.d.</td>
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### Main Scientific Goals

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

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

First plasma studies after commissioning
- 168 hours of dedicated beam time in first half of 2018
- additional beam time in parallel to FLASH1 possible, however not yet fixed

FLASHForward only experiment in the world that can access this regime, critical for high-average power applications in photon science and particle physics

- **X-100 Investigate plasma-accelerated beams for FEL gain** (PHASE II, 2020+)
Experimental programme in preparation
SEPARATED INTO CORE EXPERIMENTAL STUDIES AND PROTOTYPING

**Main scientific goals**

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### Advanced diagnostics and prototypes

**P-1** TR Spectroscopy
- Pl: P. Winkler (DESY)

**P-6** Pulsed Dipole
- Pl: S. Wesch (DESY)

**P-10** Laser-Beam Timing
- Pl: A. Knetsch (DESY)

**P-3** β-tron Radiation Det.
- Pl: S.P.D. Mangles (ICL)

**P-7** Plasma Targets
- Pl: L. Schaper (DESY)

**P-11** ICS Radiation Det.
- Pl: S. Bohlen (DESY)

**P-4** ⊥ Laser Probe
- Pl: M. Kaluza (U Jena)

**P-8** Active Plasma Lens
- Pl: J.-H. Röckemann (DESY)

**P-5** ⊥ Beam Probe
- Pl: P. Niknejad (DESY)

**P-9** X-Deflector
- Pl: R. D'Arcy (DESY)
Technical innovations at FF to face challenges in PWFA
Driver/witness-pair creation in dispersive section by variable mask

**TECHNICAL INNOVATIONS AT FF** to face challenges in PWFA

**BEAM SCRAPER FOR DRIVER/WITNESS-PAIR CREATION**


**X-2 Plasma Booster**
- PI: V. Libov (U Hamburg)

![Diagram of electron beam and scraper](image)

**Current (A)**

<table>
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**Flash 2 Forward**
Driver/witness-pair creation in dispersive section by variable mask

**TECHNICAL INNOVATIONS AT FF to FACE CHALLENGES IN PWFA**

**BEAM SCRAPER FOR DRIVER/WITNESS-PAIR CREATION**

FLASH 2

FLASH FORWARD

variable bunch separation

witness

driver

Current (A)

Witness

Driver

z (mm)

3.9 GHz cavity and compressors for beam shaping

Triangular current profile for uniform electric fields

**BEAM SHAPING FOR BEAM LOADING/TRANSFORMER RATIO CONTROL**

idea by T. Katsouleas et al., Particle Accelerators 22, 81 (1987)

Piot et al., PRL 108, 034801 (2012)

constant accelerating field $E_{zL}$

$E_{zb}$

$E_{zL} + E_{zb}$

normalized field amplitude

by C.B. Schroeder, talk at AAC

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**TECHNICAL INNOVATIONS AT FF to face challenges in PWFA**

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- **FLASH 2**
- **FLASH FORWARD**

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**X-2 Plasma Booster**

- PI: V. Libov (U Hamburg)

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Richard D’Arcy | Twitter: @FFowardDESY | Web: forward.desy.de | PITZ Collaboration Meeting, Zeuthen | December 5, 2017 | Page 14
Driver/witness-pair creation in dispersive section by variable mask

**BEAM SCRAPER FOR DRIVER/WITNESS-PAIR CREATION**

- Variable bunch separation
- Witness
- Driver

**BEAM SHAPING FOR BEAM LOADING/TRANSFORMER RATIO CONTROL**

- 3.9 GHz cavity and compressors for beam shaping
- Triangular current profile for uniform electric fields

**X-2 Plasma Booster**

- PI: V. Libov (U Hamburg)

Initial norm. emittance 2.0 µm, energy spread 0.2%, energy 1.0 GeV
Driver/witness-pair creation in dispersive section by variable mask

**Technical Innovations at FF to Face Challenges in PWFA**

**Beam Scraper for Driver/Witness-Pair Creation**

- **FLASH 2**
- **FLASH FORWARD**

Variable bunch separation

- **Driver**
- **Witness**

**Current (A)**

- **Witness**
- **Driver**

**Spatial charge distribution before plasma**

- **Witness**
- **Driver**

> Asymmetries in charge distribution seed the hosing instability

**X-2 Plasma Booster**

- PI: V. Libov (U Hamburg)
Hosing instability growth-rate and mitigation studies
TECHNICAL INNOVATIONS AT FF to face challenges in PWFA

> includes energy spread and evolution, reduces hosing (similar to BNS damping)

Betatron decoherence

Seed reduction

Hosing instability growth-rate and mitigation studies

Technical innovations at FF to face challenges in PWFA


growth-rate and mitigation studies


Full start-to-end simulations confirm hosing modes can be excited

Measurement of growth rates & hosing saturation vs. beam parameters possible at FLASHForward

Beam centroid vs. beam size at plasma entrance

Full start-to-end simulations confirm hosing modes can be excited

Measurement of growth rates & hosing saturation vs. beam parameters possible at FLASHForward
**X-band transverse deflector for femtosecond phase-space characterisation**

**TECHNICAL INNOVATIONS AT FF to FACE CHALLENGES IN PWFA**

- A collaboration between DESY, CERN, and PSI to share expertise and develop X-band technology
- A novel dual-polarisation RF deflecting cavity → tomographic reconstruction of phase space

> Resolutions for witness* and driver** beam working points:

\[
R_z = \frac{\sigma_y}{S} = \sqrt{\frac{\varepsilon_y(s)}{\beta_y(s_0)}} \frac{1}{\sin \mu_y} \frac{E}{eV_k}
\]

\[
R_\delta = \frac{\sigma_x}{|D_x|} = \sqrt{\frac{\varepsilon_x}{|D_x|}} \beta_x
\]

- \(R_t > 0.9\) fs (witness)
- \(R_t > 1.5\) fs (driver)
- \(R_\delta > 2 \times 10^{-4}\) (witness)
- \(R_\delta > 1 \times 10^{-4}\) (driver)

*\(E = 1.5\) GeV, \(\varepsilon = 0.5\) μm  
**\(E = 1.0\) GeV, \(\varepsilon = 2.0\) μm

- Prototype to be commissioned at **FLASHForward** in 2019
- Two more cavities planned on FLASH2 in early 2020
FLASHForward is a next-generation experiment for beam-driven plasma accelerator research. Work focusses on key challenges toward photon science and particle physics applications:

- High brightness beams (X-1) + plasma booster stage (X-2) as main studies
- Norm. emittance and energy spread conservation, efficiency, repetition rate
- High-temporal resolution (~ fs) diagnostics

Beamline commissioning has started in August 2017 → first plasma experiments in 2018
Molecular nature of hydrogen expected to modify electron-density distribution

**Technical Innovations at FF to Face Challenges in PWFA**

- Classical 1D simulation of H₂ fragmentation dynamics
- Short pulse regime: pure ionisation of molecule
- Long pulse regime: dissociation before ionisation
- The heavier the molecule, the longer the dissociation time

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**Plasma Targets**
- PI: L. Schaper (DESY)

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Laser intensity profile into hydrogen target

Dissociation takes time

Dissociation:

\[ \text{H}_2 \xrightarrow{4.5 \text{ eV}} \text{H} + \text{H} \]

\[ \text{H}_2 \xrightarrow{15.4 \text{ eV}} \text{H}^+ + \text{H} \]

\[ \text{H}_2 \xrightarrow{2.8 \text{ eV}} \text{H}^+ + \text{H} \]

\[ \text{H}_2 \xrightarrow{30.0 \text{ eV}} \text{H}_2^{++} \]

Fragmentation dynamics

P-7
Molecular nature of hydrogen expected to modify electron-density distribution

**TECHNICAL INNOVATIONS AT FF TO FACE CHALLENGES IN PWFA**

- Classical 1D simulation of H₂ fragmentation dynamics
- Short pulse regime: pure ionization of molecule
- Long pulse regime: dissociation before ionization
- The heavier the molecule, the longer the dissociation time

Experimental verification in the works...

P-7 Plasma Targets
  - PI: L. Schaper (DESY)
Figure 2: Snapshots from a PIC simulation showing the process of DDR injections

Figure 3: The resulting electron profile of the injected bunch seen in figures 1 and 2.
Start-to-end simulations: Hosing instability in PWFA
Centroid equations

**Beam centroid equation**

\[
\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 (X_b - X_c) = 0
\]

**Channel centroid equation** assuming linear plasma sheath response*

\[
\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2}{2} (X_c - X_b) = 0
\]

**Channel centroid equation** including relativistic sheath electrons and varying current and blowout radius along beam**

\[
\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2 c_v(\xi)c_r(\xi)}{2} (X_c - X_b) = 0
\]

\[
c_r(\xi) = 4I_b(\xi)/I_a(k_p R(\xi))^2
\]

\[
c_v(\xi) = 1/(1 + \psi(\xi))
\]

Beam centroid equation ***

\[
\frac{\partial^2 X_b}{\partial t^2} + \frac{\omega_\beta^2}{\omega_{\beta,0}} (\epsilon + \kappa_1 \Delta \gamma^2) \frac{\partial X_b}{\partial t} + \frac{\omega_\beta^2}{\omega_{\beta,0}} (1 + \kappa_2 \Delta \gamma^2) (X_b - X_c) = 0
\]

Uncorr. energy spread: \( \Delta \gamma = \sigma_\gamma/\gamma_0 \)

Rel. acceleration rate: \( \epsilon = -\sqrt{2/\gamma_0} E_x/E_0 \)

Coefficients:

\[
\kappa_1 = (\omega_\beta/\omega_{\beta,0}) - (\omega_\beta/\omega_{\beta,0})^2/\epsilon
\]

\[
\kappa_2 = (\omega_\beta/\omega_{\beta,0})^3/2 - (\omega_\beta/\omega_{\beta,0})^4/4
\]

Includes the effects of the energy spread and evolution

*** T. J. Mehrling et al., PRL 118, 174801 (2017)

Dramatic implications for PWFA

Beam centroid deviations are amplified exponentially in time and along the beam!

Excellent agreement between analytical estimates, numerical solution and PIC*

Considered beam:
Init. centroid: $k_pX_{b,0}(\xi) = 0.01 \times \Theta(\xi)$
Peak current: $I_b = I_A/4$
Dimensions: $k_p\sigma_x = k_p\sigma_y = 0.1$, $k_p\sigma_z = 1.0$

Considered cases
decoupling time $\tau_{\alpha} \approx \frac{3\pi}{2\Delta \varepsilon}$
damping time $t_{\text{damp}} \approx \frac{\pi}{\omega_{\beta,0} \sigma_\gamma}$

C1: No energy change
C2: Energy change
C3: Energy change & spread

Tailored density transition for hosing mitigation

Optimum taper parameter $\lambda_{\text{opt}} \approx L/\sqrt{k_{\beta,0}L}$

$n(z) = \begin{cases} 0 & \text{if } z \leq z_v, \\ n_0 & \text{if } z_v < z \leq z_0, \\ n_0(1 - (z - z_0)/\lambda)^{-4} & \text{if } z > z_0, \end{cases}$

Betatron wavenumber: $k_\beta = k_{\beta,0} \sqrt{\frac{n}{n_0}}$

Significant mitigation of hose instability!*
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

Hosing instability in plasma

- triggered by centroid offsets along beam
- may severely affect plasma accelerator performance
- mitigation crucial → various concepts under investigation
RF 2.0kA - R56 zero

J. Zemella and V. Libov
Simulation snapshots

Centroid evolution

Centroid oscillations are completely suppressed for higher emittance beams

(a): 2kA
(b): 2kA (emit. spoiler)
(c): 3kA
(d): 3kA (emit. spoiler)
Title Text

beams at plasma exit:
- \( \sim \% \) level energy spread
- \( \leq \) mm beta function, \( \sim \) mrad divergence

leads to transverse emittance growth in free drift

\[ \Rightarrow \] K. Floettmann, Phys. Rev. STAB 6, 034202 (2003)


Phase space ellipses during drift
Emittance growth depending on transition length

\[ \epsilon_n(z) = (U_{x0} \epsilon_{x0} + U_{y0} \epsilon_{y0} + \epsilon^2)(1 + L) \]

Plasma-to-vacuum transition \( \gg \) beta for emittance preservation

Strong quadrupoles for beam capturing required.

Example: 1 GeV beam with 100 T/m quads fully captured only \( \sim 1 \) m behind plasma \( \Rightarrow \) emittance growth considerable