Richard D’Arcy  
FLASHFORWARD  
Project Coordinator | Group Leader for Beam-Driven Plasma Accelerators  
DESY. Accelerator Division
Acknowledgements

FLASHFORWARD SCIENTIFIC TEAM

Richard D’Arcy (Project Coordinator)
Stephan Wesch (Technical Coordinator)
Judita Beinortaite
Jonas Björkland Svensson
Simon Bohlen
Lewis Boulton
James Chappell
Jimmy Garland (PI)
Pau Gonzalez
Julian Hörsch
Carl Lindstrøm (PI)
Gregor Loisch (PI)
Felipe Peña Asmus
Kris Pöder
Adam Scaachi
Sarah Schröder
Bridget Sheeran
Jon Wood (PI)

THEORY GROUP

Maxence Thévenet
Gregory Boyle
Severin Diederichs
Mathis Mewes

...and the technical groups from the accelerator and particle physics divisions!
Acknowledgements

**FLASHForward**

**SCIENTIFIC TEAM**

Richard D’Arcy (Project Coordinator)
Stephan Wesch (Technical Coordinator)
Judita Beinortaite
Jonas Björklund Svensson
Simon Bohlen
Lewis Boulton
James Chappell
Jimmy Garland (PI)
Pau Gonzalez
Julian Hörsch
Carl Lindstrøm (PI)
Gregor Loisch (PI)
Felipe Peña Asmus
Kris Põder
Adam Scaachi
Sarah Schröder
Bridget Sheeran
Jon Wood (PI)

**THEORY GROUP**

Maxence Thévenet
Gregory Boyle
Severin Diederichs
Mathis Mewes

...and the technical groups from the accelerator and particle physics divisions!
Limitations of current accelerator technology

(Superconducting) Radio-frequency cavity

Limited by electrical breakdown to $\sigma(100 \, \text{MV/m})$
Limitations of current accelerator technology

(Superconducting) Radio-frequency cavity

Limited by electrical breakdown to $\sigma(100 \text{ MV/m})$

1 TeV $\text{e}^+\text{e}^-$ collider example

→ tens of km of cavities
→ >10 billion euros

IS A PARADIGM SHIFT REQUIRED?
Plasma accelerators are a centimeter-scale source of GeV beams.

Plasma wakefields can sustain accelerating fields of up to \(~1-100\) GV/m, \(\times 1000\) more than RF technology.

Electron beam can be externally injected or formed from trapped plasma electrons (internal injection).

Driver (laser or charged-particles)

Witness (electrons)

Depleted driver

FBPIC simulation by Ángel Ferran Pousa (2020)
Our customers: high-energy physics and photon science

> High energy physics and photon science demand high(est) energy at low cost.

> Solution: Plasma accelerators — significantly higher acceleration gradients.

> Simultaneously, particle colliders have strict demands for luminosity: (FELs have similar demands for brightness)

\[
\mathcal{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx} \epsilon_{ny}}}
\]

High repetition rate  
High energy efficiency  
Low energy spread  
(luminosity spectrum, final focusing)  
Low emittance

> Energy efficiency motivates use of beam-driven plasma acceleration.

\[\eta = \eta_{\text{wall} \rightarrow DB} \times \eta_{DB \rightarrow WB}\]

Luminosity distribution across collision energies.  

Beam-drivers are orders of magnitude more efficient than laser-drivers (for now)
Our customers: high-energy physics and photon science

- High energy physics and photon science demand high(est) energy at low cost.
  - Solution: Plasma accelerators — significantly higher acceleration gradients.

- Simultaneously, particle colliders have strict demands for luminosity: (FELs have similar demands for brightness)

  \[
  \mathcal{L} = \frac{H_D}{8\pi m c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx} \epsilon_{ny}}}
  \]

  - High repetition rate
  - High energy efficiency
  - Low energy spread (luminosity spectrum, final focusing)
  - Low emittance

Develop a self-consistent plasma-accelerator stage with high efficiency, high quality, and high average power
FLASHFORWARD utilises FLASH superconducting accelerator
Plasma accelerator tightly integrated into facility and benefits from Free-Electron-Laser beam quality

FLASH is an FEL user facility
- 10% of beam time dedicated to generic accelerator research

Superconducting accelerator based on ILC/XFEL technology
- \( \lesssim 1.25 \) GeV energy with \( \sim \)nC charge at few 100 fs bunch duration
- \( \sim 2 \) \( \mu \)m trans. norm. emittance
- \( \sim 10 \) kW average beam power, MHz repetition rate in 10 Hz bursts
- exquisite stability by advanced feedback/feedforward systems

Unique opportunities for plasma accelerator science
FLASHFORWARD utilises FLASH superconducting accelerator

Plasma accelerator tightly integrated into facility and benefits from Free-Electron Laser beam quality
Advanced collimator system for longitudinal bunch shaping

FLASHFORWARD beamline features innovative components and methods

Three energy collimators:
(1) Tail (high energy)
(2) Head (low energy)
(3) Central notch (two bunches)

µm-precision movements allows for precise bunch shaping (in conjunction with FLASH compressors and 3.9 GHz cavity)
Two discharge capillaries provide density-controlled plasma

FLASHFORWARD beamline features innovative components and methods


High-voltage discharge

Sapphire capillaries
(50 mm and 195 mm long)

Gases: He, Ne, Ar, Kr, H (soon!)
Two electron spectrometers used for diagnostic purposes

FLASHFORWARD beamline features innovative components and methods

Imaging spectrometer

High-resolution, narrow-band screen for mm-mrad emittance measurements

Low-resolution, broad-band screen for MeV—GeV energy range
1.1 GeV energy gain and loss achieved in a 195 mm plasma module

Plasma accelerator essentials — demonstrating 6 GV/m field strength

Taking plasma accelerator technology from ‘academia to application’ doesn’t end with high-gradient acceleration

Energy doubling to 2.2 GeV → plasma booster

Energy extraction → plasma beam dump

Initial energy: 1100 MeV

First realisation of deceleration to rest
FLASHForward™: Beam-driven plasma-wakefield experimentation

Primary goals of FLASHFORWARD™

Develop a self-consistent plasma-accelerator stage with high efficiency, high quality, and high average power

- High efficiency
  - Transfer efficiency
  - Driver depletion

- High beam quality
  - Energy-spread preservation
  - Emittance preservation

- High average power
  - High repetition rate
Develop a self-consistent plasma-accelerator stage with high efficiency, high quality, and high average power

- High efficiency
  - Transfer efficiency
    - Driver depletion
  - Energy-spread preservation
    - Emittance preservation

- High beam quality

- High average power
  - High repetition rate
Optimal beam loading enables uniform and efficient acceleration

> Problem 1: Compared to RF cavities ($Q \sim 10^4$–$10^{10}$), the electric fields in a plasma decay very rapidly ($Q \sim 1$–$10$).

> The energy needs to be extracted very quickly—ideally within the first oscillation.

Optimal beam loading enables uniform and efficient acceleration

> **Problem 1:** Compared to RF cavities ($Q \sim 10^4$–$10^{10}$), the electric fields in a plasma decay very rapidly ($Q \sim 1$–$10$).

> The energy needs to be extracted very quickly —ideally within the first oscillation.

> **Solution:** Beam loading

The trailing-bunch wakefield “destructively interferes” with the driver wakefield—extracting energy.

Optimal beam loading enables uniform and efficient acceleration

> **Problem 1**: Compared to RF cavities ($Q \sim 10^4$–$10^{10}$), the electric fields in a plasma decay very rapidly ($Q \sim 1$–$10$).

> The energy needs to be extracted very quickly —ideally within the first oscillation.

> **Solution**: Beam loading

The trailing-bunch wakefield “destructively interferes” with the driver wakefield—extracting energy.

> **Problem 2**: To extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).

> Large energy spread is induced.

> **Not (easily) possible**: Dechirping

---

Optimal beam loading enables uniform and efficient acceleration

> **Problem 1:** Compared to RF cavities ($Q \sim 10^4\text{--}10^{10}$), the electric fields in a plasma decay very rapidly ($Q \sim 1\text{--}10$).

  > The energy needs to be extracted very quickly—ideally within the first oscillation.

  > **Solution:** Beam loading
  
  The trailing-bunch wakefield “destructively interferes” with the driver wakefield—extracting energy.

> **Problem 2:** To extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).

  > Large energy spread is induced.

  > **Solution:** Optimal beam loading
  
  The current profile of the trailing bunch is *precisely tailored* to exactly flatten the wakefield.

  > This requires extremely precise control of the current profile.

  > **FLASHForward** provides the tools to do that.
High-resolution plasma wakefield sampling demonstrated
Opens a pathway to targeted and precise field manipulation

> Beam itself acts as a probe
  → measures in-situ (under actual operation conditions) the effective field acting on beam with µm / fs resolution

S. Schröder et al., Nat. Commun. 11, 5984 (2020)
High-resolution plasma wakefield sampling demonstrated
Opens a pathway to targeted and precise field manipulation

> Beam itself acts as a probe
→ measures in-situ (under actual operation conditions) the effective field acting on beam with \( \mu \text{m} / \text{fs} \) resolution

S. Schröder et al., Nat. Commun. 11, 5984 (2020)
Loading the wakefield and beam shaping flattens the gradient

Direct visualization of electric-field control by wakefield sampling

C.A. Lindstrøm et al., PRL 126, 014801 (2021)

- Accelerating gradient of 1.3 GV/m
- No charge loss
- Few-percent-level wakefield flattening

High-quality, efficient acceleration for sustainable applications
Beam-loading facilitates 42% energy-transfer efficiency, 0.2% energy spread with full charge coupling

C.A. Lindstrøm et al., PRL 126, 014801 (2021)

- Accelerating gradient of 1.3 GV/m
- No charge loss
- Few-percent-level wakefield flattening

- 0.2% energy spread (input 0.16%)
  (improvement by factor 10 over state-of-the-art)

- (42±4)% energy transfer efficiency
  (improvement by factor 3 over state-of-the-art)
FLASHFORWARD roadmap aims at 10 kW with high beam quality

Plan covers major plasma accelerator challenges

- **2018**
  - Plasma dechirper

- **2019**
  - Energy depletion and energy doubling

- **2020**
  - Wakefield sampling
    - D'Arcy *et al.*, *PRL* 122, 034801 (2019)
    - Lindstrom *et al.*, *PRL* 126, 014801 (2021)

- **2022**
  - Energy spread preservation by beam loading control
    - Lindstrom *et al.*, *PRL* 126, 014801 (2021)
  - Emittance preservation

- **2024**
  - Detection of slice properties with fs resolution
  - kHz-to-GHz plasma response

- **2026**
  - 10 kW avg. power operation

- **2030**
FLASHFORWARD roadmap aims at 10 kW with high beam quality

Plan covers major plasma accelerator challenges

2018
- Plasma dechirper
  - D’Arcy et al., PRL 122, 034801 (2019)

2019
- Energy depletion and energy doubling
- Wakefield sampling
  - Schröder et al., Nat. Commun. 11 5984 (2020)

2020
- Energy spread preservation by beam loading control
  - Lindstrøm et al., PRL 126, 014801 (2021)
- Emittance preservation

2022
- High overall efficiency and gain for sustainable operation
- Detection of slice properties with fs resolution

2024
- kHz-to-GHz plasma response

2026
- 10 kW avg. power operation

2030
- 10 kW stage with 50% efficiency & beam quality conservation

→ FLASH: increase FEL energies, access oxygen K-edge at 2.33 nm wavelength
Progress in Plasma-Accelerator R&D at **FLASHFORWARD**

**Summary and outlook**

Develop a self-consistent plasma-accelerator stage with high efficiency, high quality, and high average power.

- High efficiency
- High beam quality
- High average power

- Transfer efficiency ✓
- Driver depletion □
- Energy-spread preservation ✓
- Emittance preservation □
- High repetition rate □

- Impactful and exciting research programme will help advance plasma accelerators to application-readiness