Probing Ion-motion Recovery in a Beam-driven Plasma-wakefield Accelerator

Judita Beinortaitė*[1,2], James Chappell[3], Matthew James Garland[1], Carl A. Lindstrøm[1], Gregor Loisch[1], Sarah Schröder[1], Stephan Wesch[1], Matthew Wing[1,2], Jens Osterhoff[1], and Richard D'Arcy[1]
1 DESY, Hamburg, Germany; 2 University College London, London, UK; 3 University of Oxford, Oxford, UK

FLASHFORWARD

1. High-repetition-rate requirements

PWFA in future facilities

- High-repetition rate needs to be achieved in PWFA for future applicability.

number of bunches per macro-pulse

$$\mathcal{L} \propto n_b f_p$$

the rate of macro-pulses per second

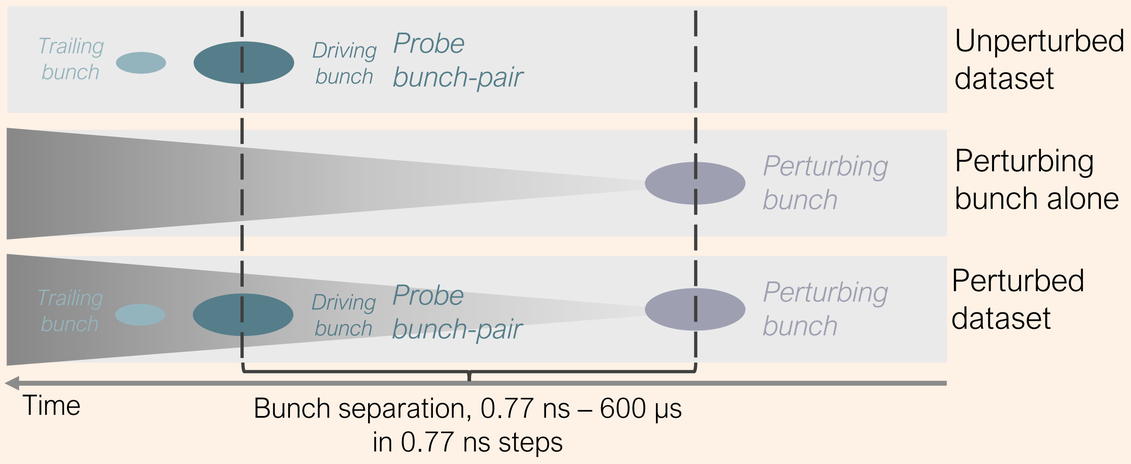
Facility	Bunch separation within a macro-pulse	Macro-pulse repetition rate	Number of bunches per macro-pulse
ILC[1]	500 ns	5 Hz	1000-5400
CLIC[2]	0.5 ns	50 Hz	312
State-of-the-art PWFA	100 ms	10 Hz	1

Table 1

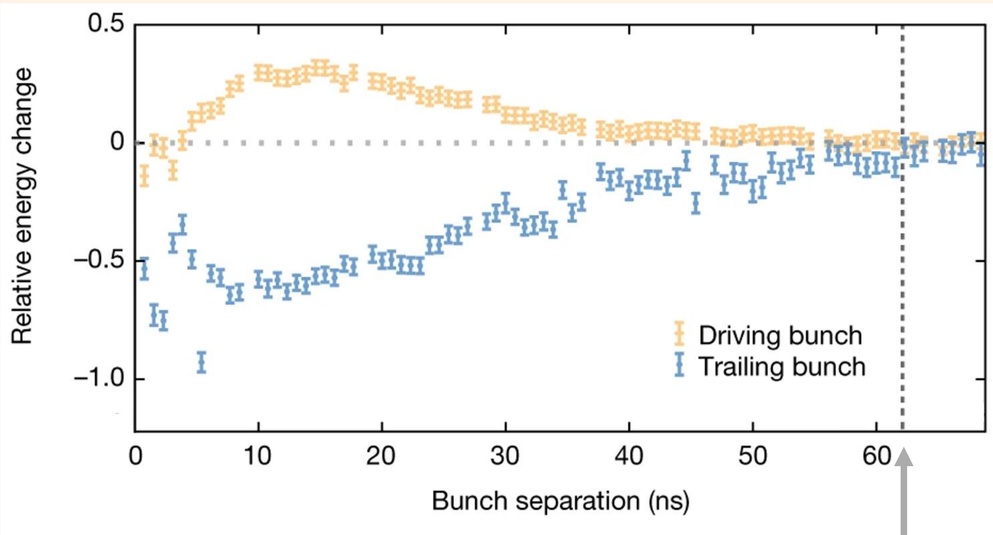
2. Measuring plasma recovery time

Recent results

Probe-bunch technique for observing the long-term ion motion[5]



- Same plasma conditions need to be recovered before the next acceleration event.
- **Long-term ion motion** is the most dominant limitation in ns-µs timescales[3,4,5].



$$R = \frac{E_P - E_U}{E_U}$$

E_P - perturbed energy
E_U - unperturbed energy

Recovery time
63 ns in Argon

3. Ion Acoustic Wave Dynamics

Modelling the recovery of plasma from on-axis moving ion density peak

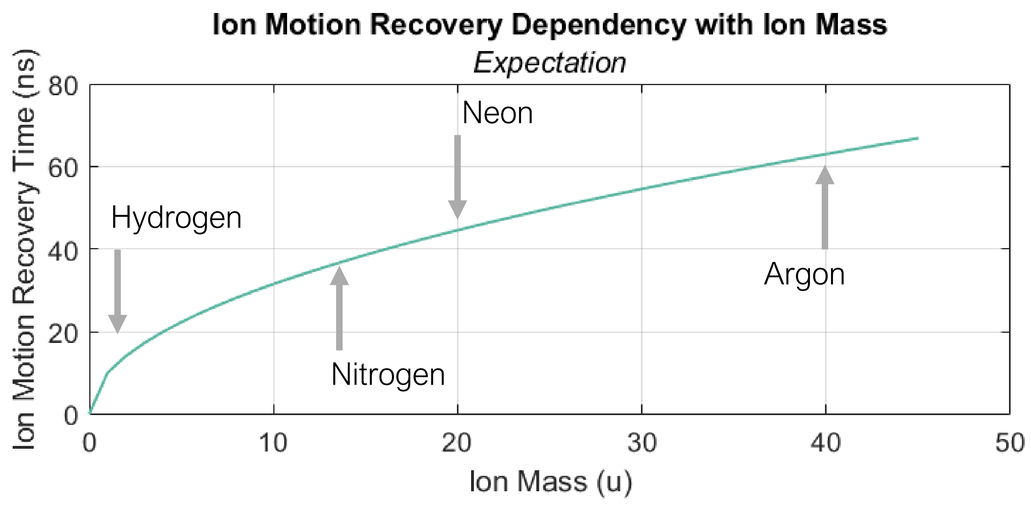
- Ion compression is counteracted by thermal motion of ions and ion electrostatic forces.[6]
- Ion acoustic velocity → describes the timescale of the recovery in plasma.
- **Reduced ion mass → reduce the recovery time.**
- Assumption: **all other parameters stay the same.**
- Deviations from this assumption give insight to additional physics.

$$v \sim \sqrt{\frac{k_B T_e + \gamma_i k_B T_i}{m_i}}$$

$$v \sim \sqrt{\frac{k_B T_e}{m_i}}$$

$$\tau_{H_2} = \tau_{Ar}\sqrt{\frac{m_{H_2}}{m_{Ar}}},$$

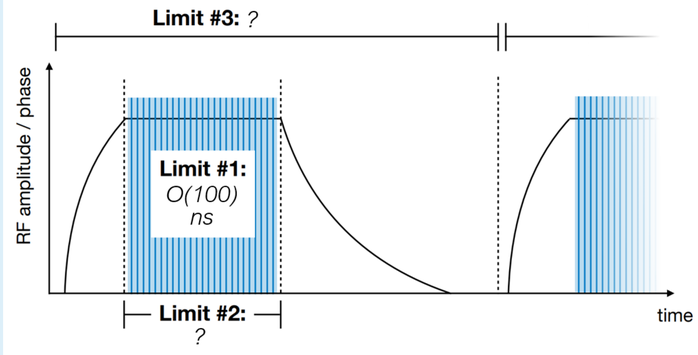
$$\tau_{H_2} = 63\sqrt{\frac{1}{40}} \approx 10\ ns.$$

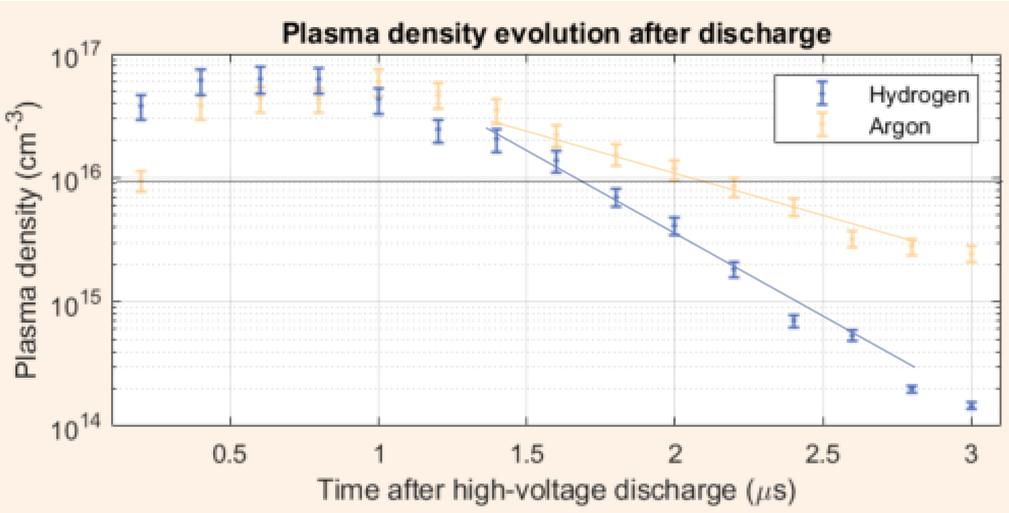


4. Electron bunch pattern

Electron bunch repetition-rate in future PWFA facilities

- $\tau_{H_2} = 10\ ns \rightarrow$ plasma is not a fundamental limit for future facilities.
- For future accelerator luminosities → 10,000 bunches per second.
- 10 ns plasma recovery time → flexibility in bunch train shaping.
- Example: 100 bunches at 100 Hz.





5. Plasma characterisation

Looking for equivalent recovery conditions in two different gases

- Argon is doped with 3% hydrogen → spectral H-alpha line broadening → plasma density value.[7]
- Hydrogen plasma density declines quicker than in Argon.
- Operational density 5e15-2e16 cm^{-3}.
- Same high-voltage discharge timing jitter for H_2 and Ar → larger jitter for H_2 density.
- Characterising plasma this way allows to establish comparable conditions in two gases.
- Thus, recovery time reduction based on ion mass could be observed.

6. Outlook

- The infrastructure to explore high-repetition-rate related dynamics in plasma exists at FLASHForward.
- This includes generating Hydrogen plasma, and FLASH electrons from GHz-double-bunches or MHz-bunch-trains.
- Different gas plasma settings in the capillary are being measured and analysed.
- Characterised plasma is necessary to make plasma recovery time reduction experiments.
- Beam-based measurements will start after the FLASH and FLASHForward shutdown upgrade: October 2022.

References:
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[4] M. F. Gilljohann et al. Physical Review X 9.011046 (2019).
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* Contact: judita.beinortaite@desy.de | http://forward.desy.de

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High Energy Physics Group,
Department of Physics and Astronomy
University College London

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