# Plasma density and ionisation degree evolution with long-term ion motion in a beam-driven plasma-wakefield accelerator

**Judita Beinortaitė**

FLASHFORWARD▸▸

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HELMHOLTZ

iFAST

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UCL

DESY.

# High-repetition-rate requirements

## PWFA in future facilities

- High-repetition-rate PWFA needed in future facilities.

$$\mathcal{L} \propto f_{rep}$$

$$B_{int} \propto f_{rep}$$

$$\boxed{f_{rep} = n_b f_p}$$

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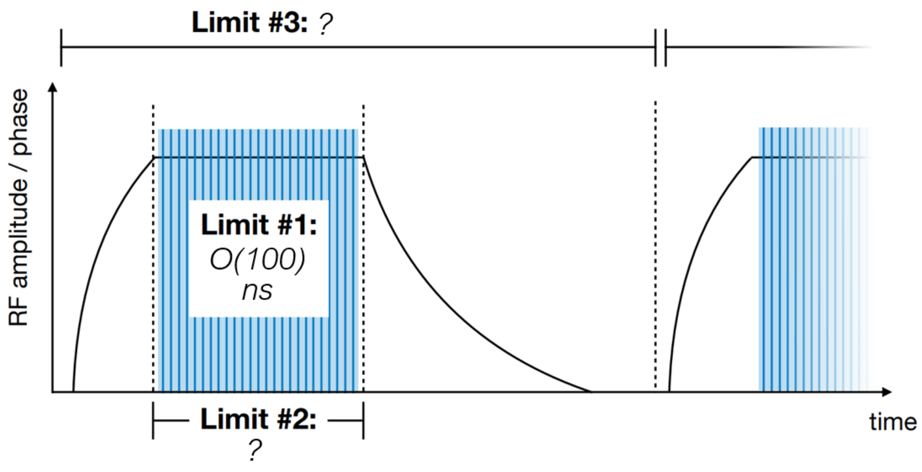

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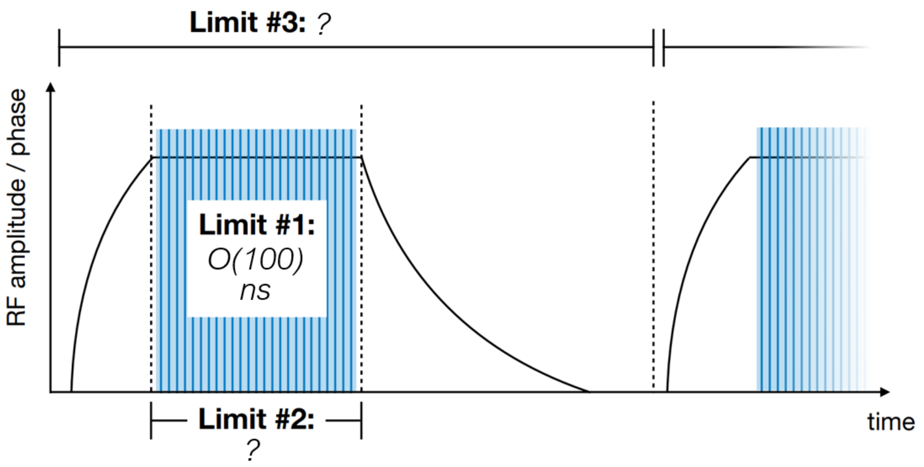
| Facility | Bunch separation within a macro-pulse (ns) | Macro-pulse repetition rate (Hz) | Number of bunches per macro-pulse |
|---|---|---|---|
| ILC[1] | 500 | 5 | 1000-5400 |
| CLIC[2] | 0.5 | 50 | 312 |
| FLASH[3] | 1000 | 10 | 800 |
| PWFA | 100 000 000 | 10 | 1 |
| PWFA(2023)[4] | 1000 | 1 | 12 |

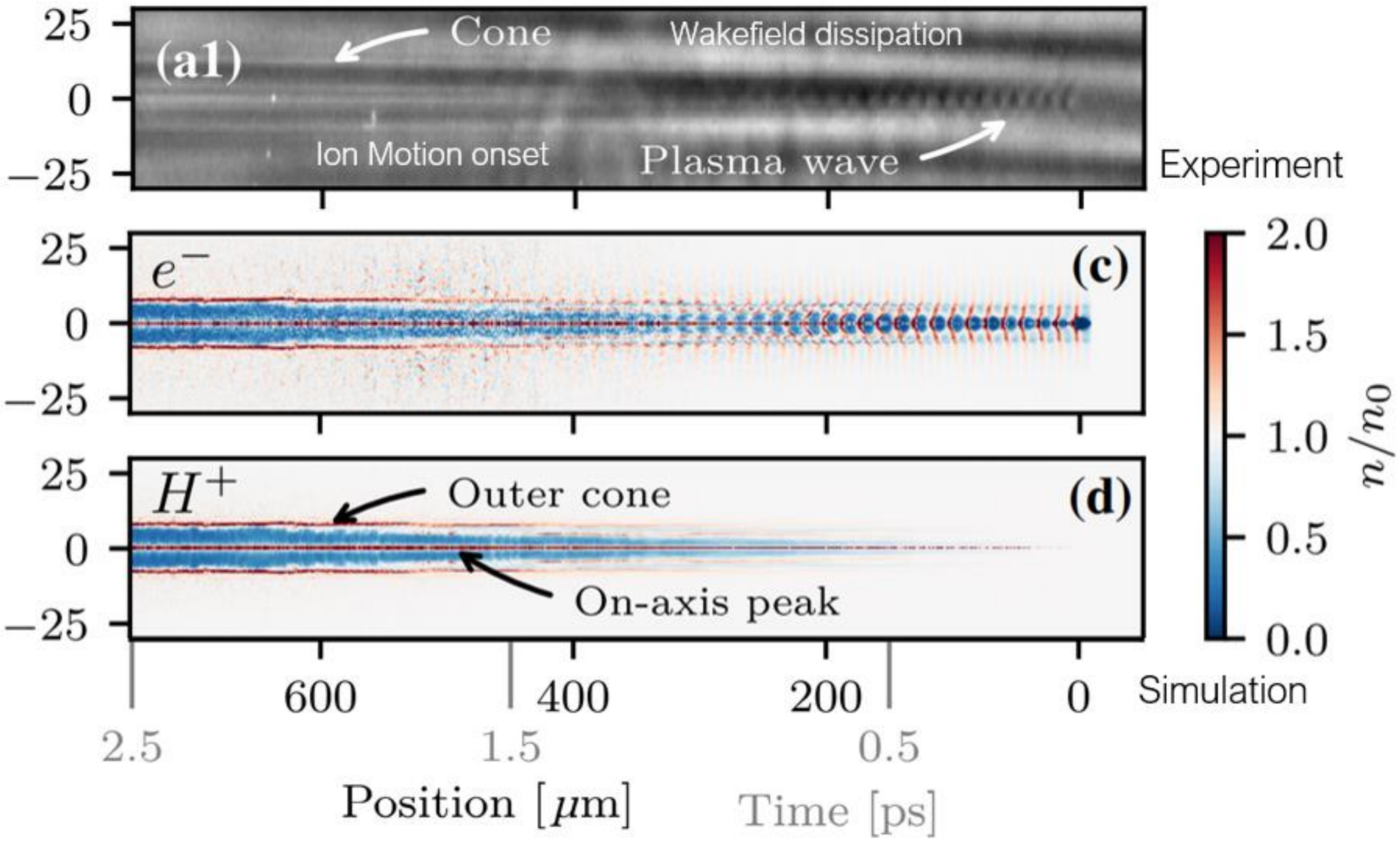
[1] ILC. arXiv:0712.1950v1 (2007).
[2] CLIC. CERN-2012-007 (2012).
[3] FLASH. New J. Phys. 18 062002 (2016).
[4] G. Loisch, talk in WG1, 21/09/2023, 16:25.



# Long-term Ion Motion

## Plasma dynamics in nanoseconds-microseconds timescale

- Previous work on ion motion:
  - Post-wakefield ion motion observed.




Ion-channel formation from a plasma wakefield.
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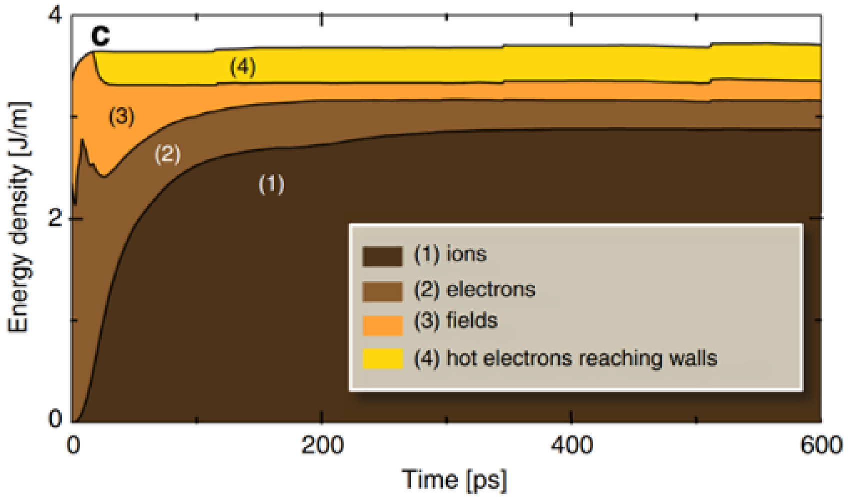


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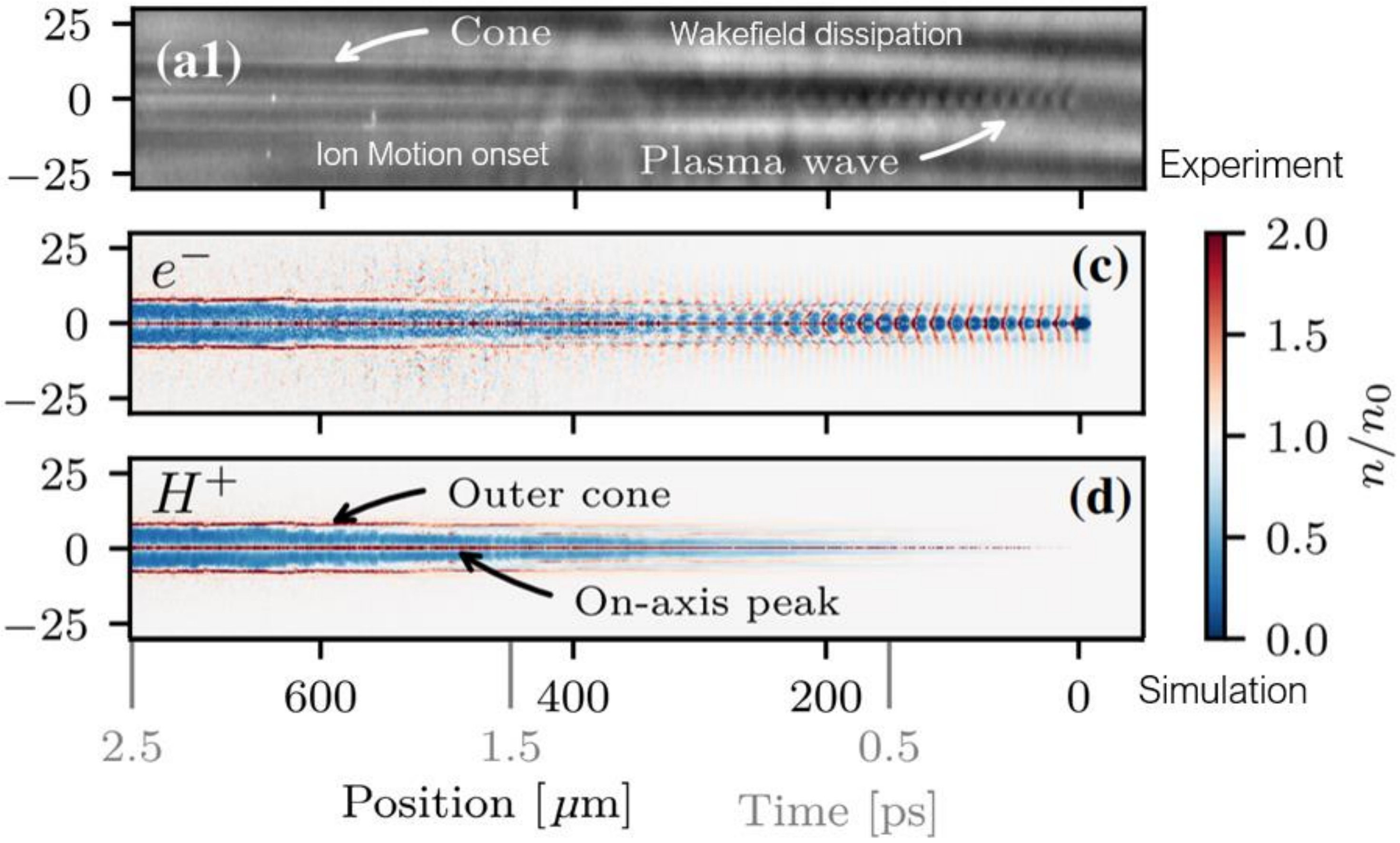


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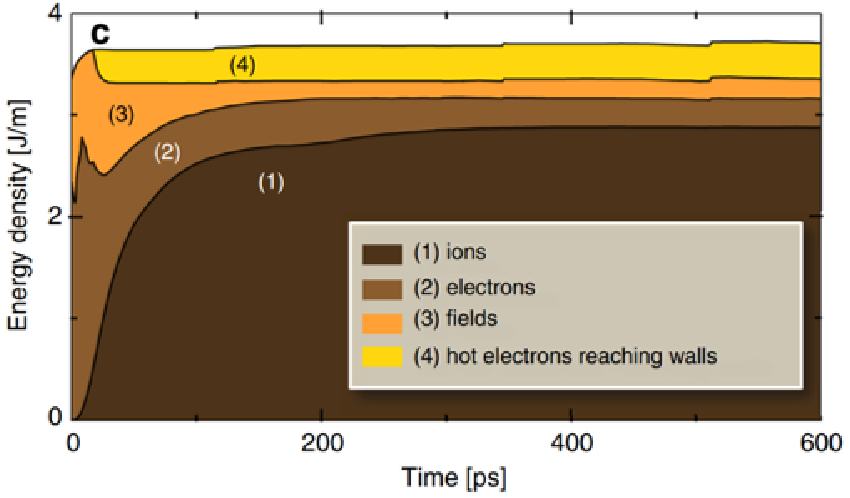
  - Ions carry most deposited energy.
    - (on 1 ns timescale).
- How long does it last?
  - Cannot simulate with Particle-In-Cell.
  - Need measurements.

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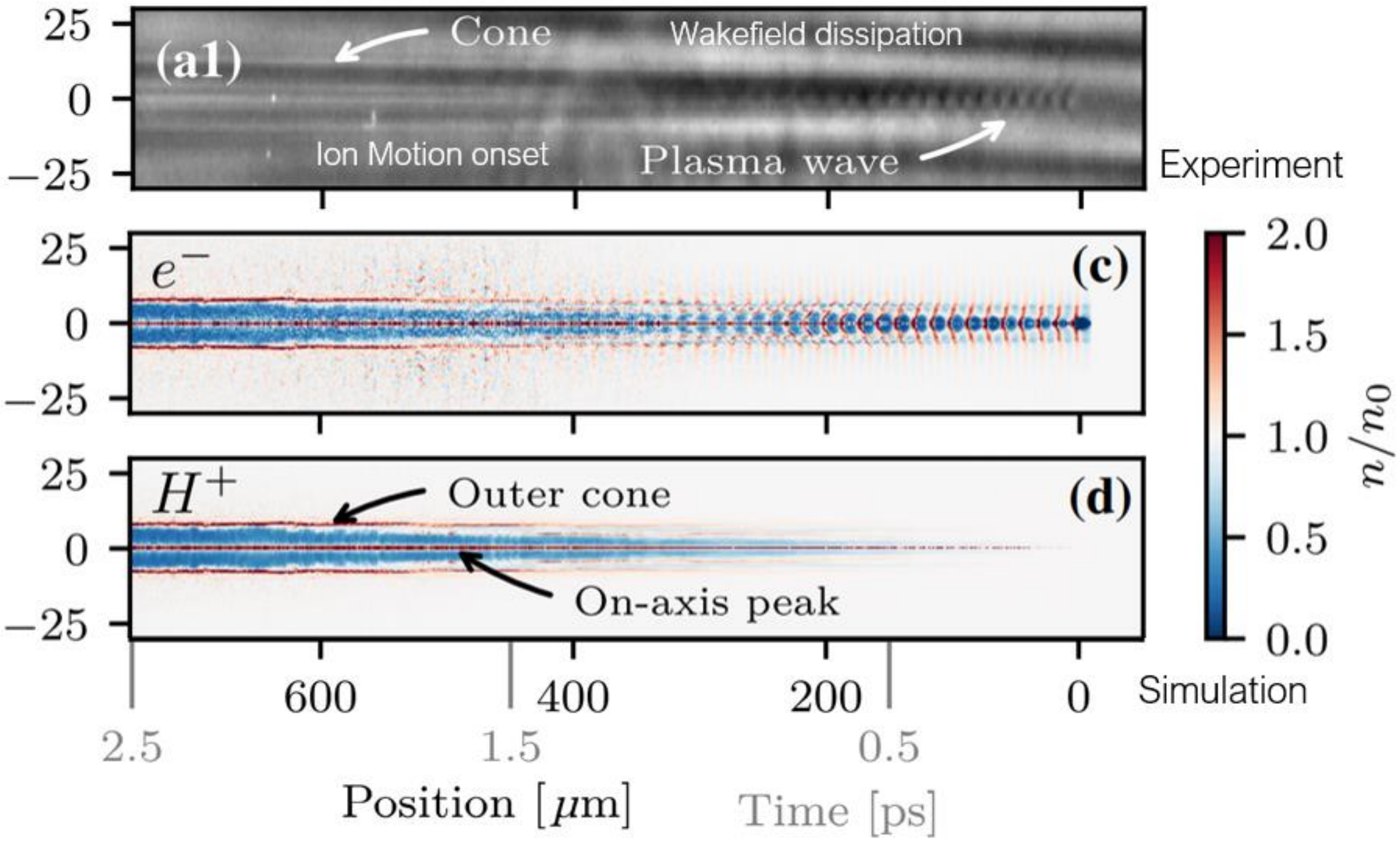


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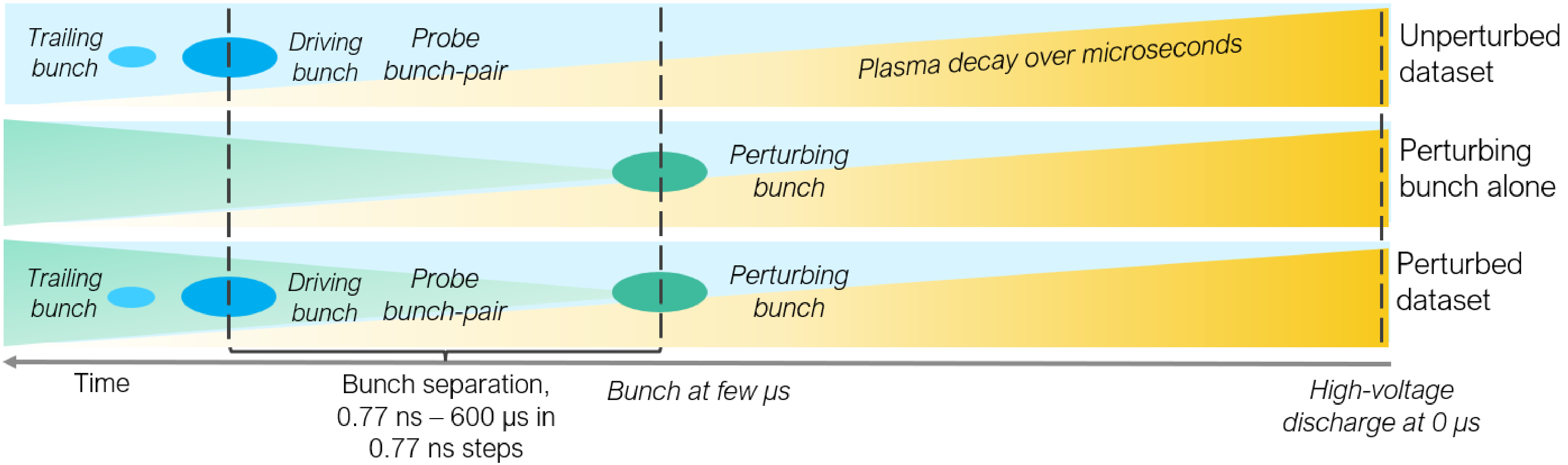
# Probing Long-term Ion Motion at FLASHForward►►

## Recovery time of a plasma-wakefield accelerator

- Long-term Ion-motion is caused by the perturbing bunch.
- The effects of ion motion are observed on the probe bunch.




Probe-bunch technique for observing the long-term ion motion.
*R. D'Arcy et al., Nature 603, 58 62 (2022)*

# Probing Long-term Ion Motion at FLASHForward▶▶

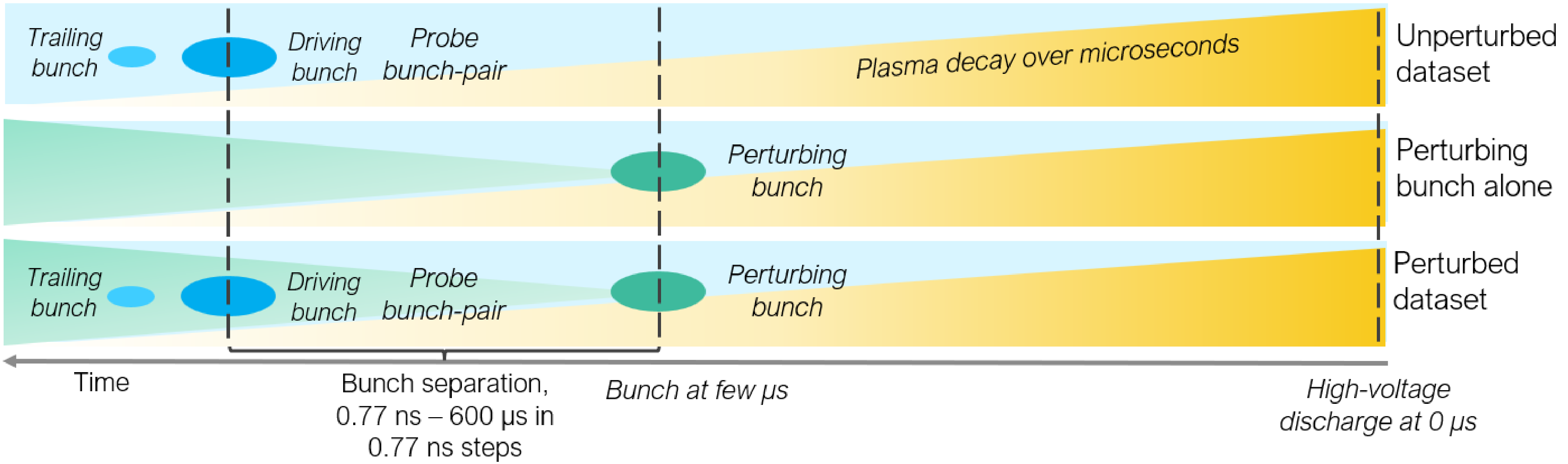
## Recovery time of a plasma-wakefield accelerator

- Long-term Ion-motion is caused by the perturbing bunch.
- The effects of ion motion are observed on the probe bunch.
- Comparison between Unperturbed and Perturbed datasets:
  - Evolution of ion motion,
  - Time of ion motion recovery.

$$t = t_{recovery}$$

if

$$\begin{cases} E_{gain}^{pert} = E_{gain}^{unpert} & \text{trailing bunch} \\ E_{loss}^{pert} = E_{loss}^{unpert} & \text{driving bunch} \end{cases}$$

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# Pump-probe electrons at FLASHFORWARD▸▸

- 1 GeV, 1 nC, up to 10 Hz electron beams from FLASH[1] LINAC – soft-X ray free-electron laser at DESY.

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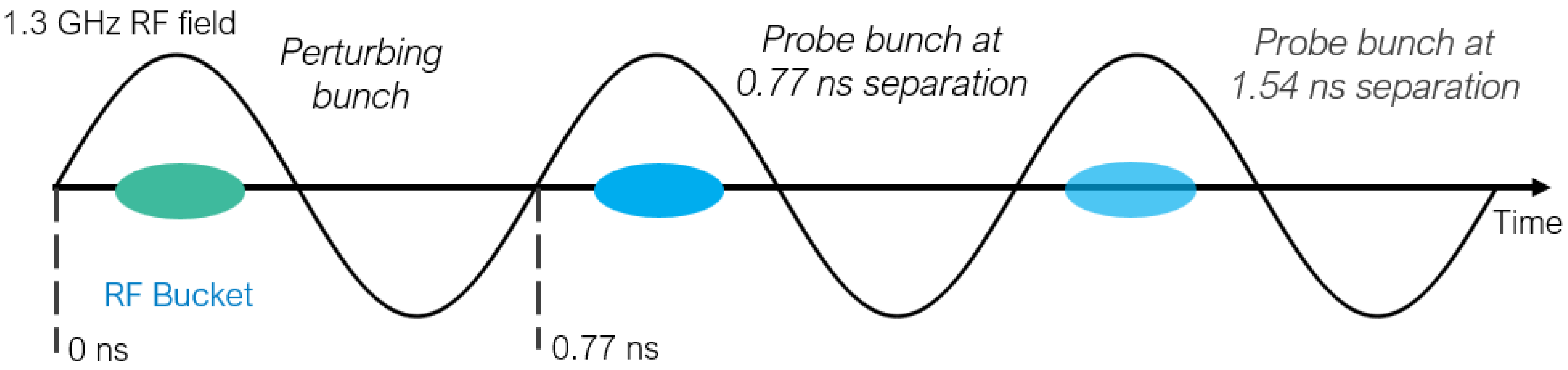
# Pump-probe electrons at FLASHFORWARD►►

- 1 GeV, 1 nC, up to 10 Hz electron beams from FLASH[1] LINAC – soft-X ray free-electron laser at DESY.
- 0.77 ns two-bunch separation:
  - Stems from 1.3 GHz RF frequency.
  - Allows FF>> to study high-repetition-rate operation in PWFA.

Conceptual representation of the two-bunch acceleration method.

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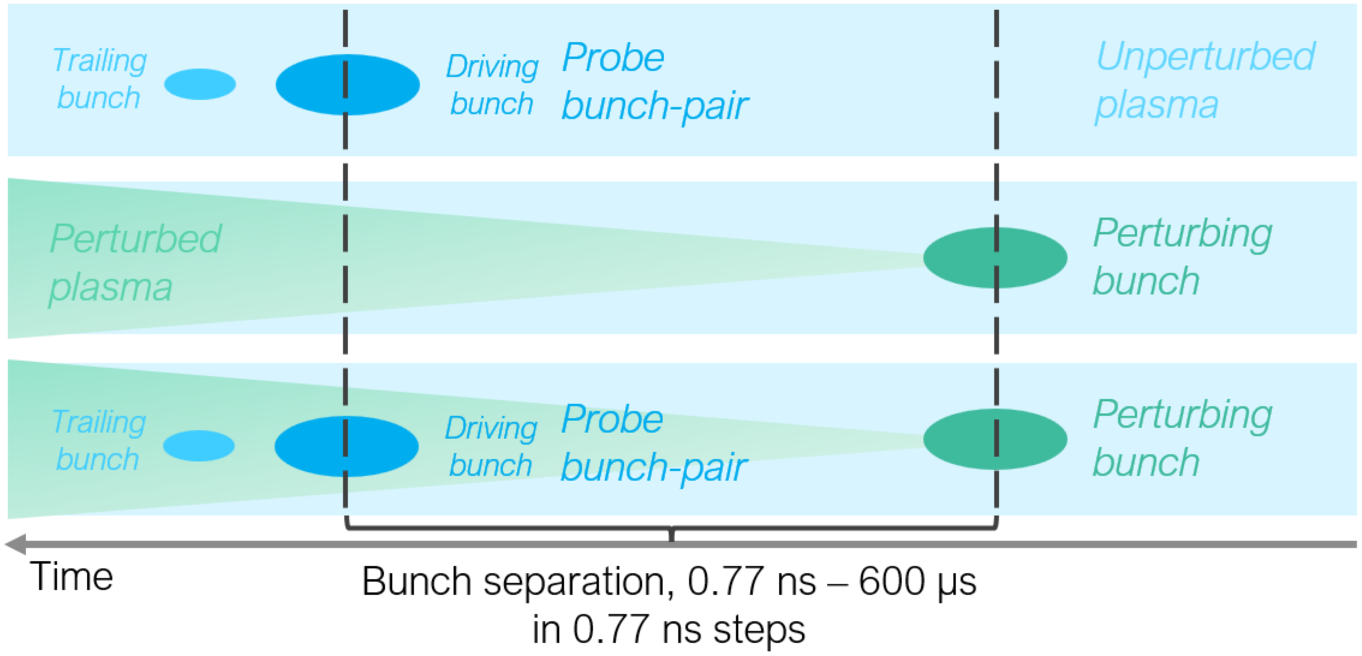
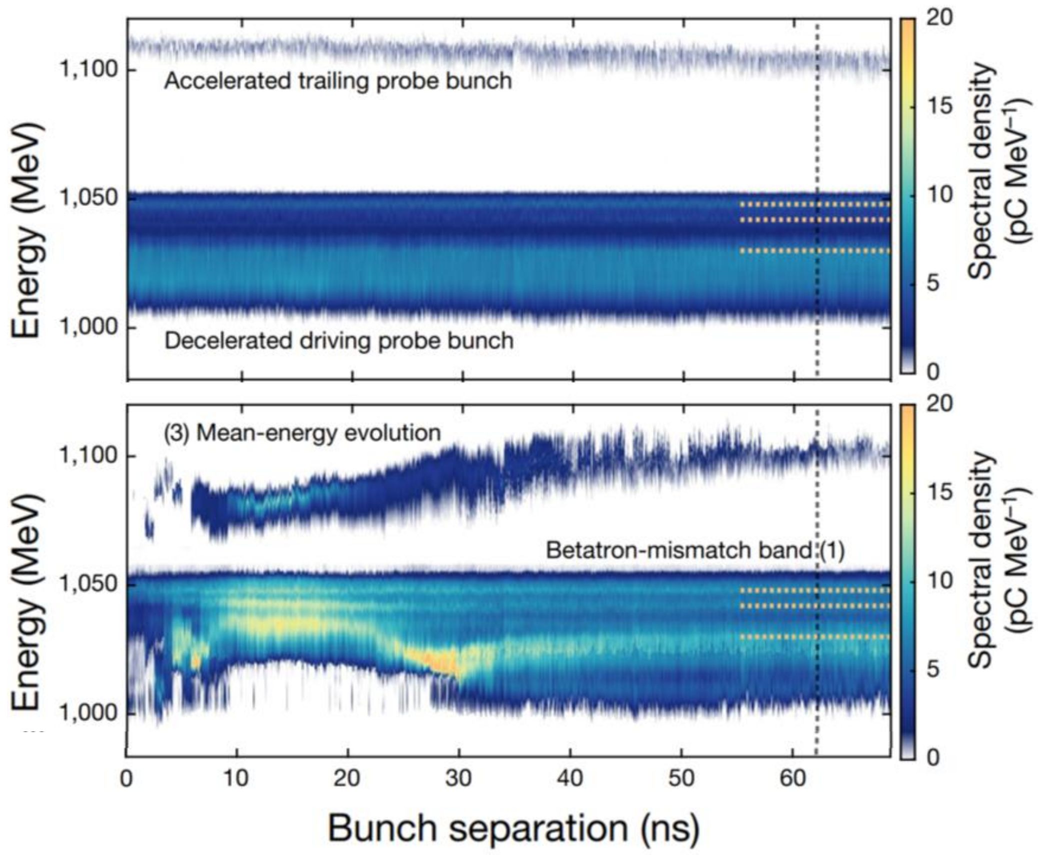
# Recovery time measurement

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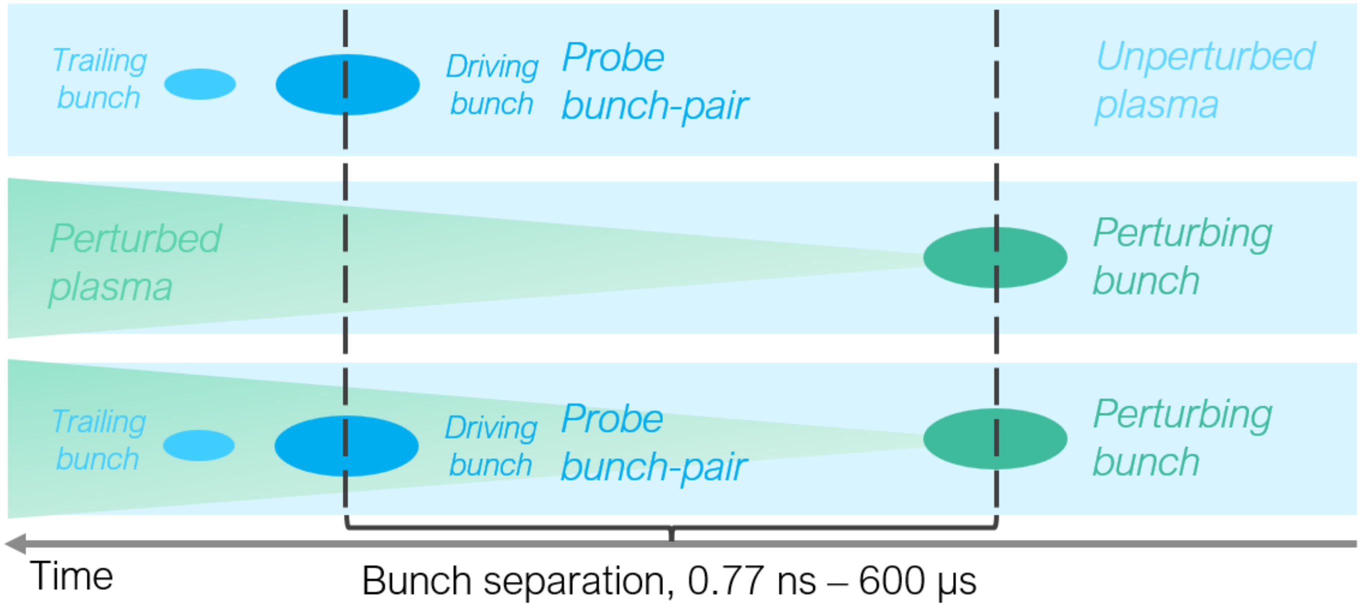


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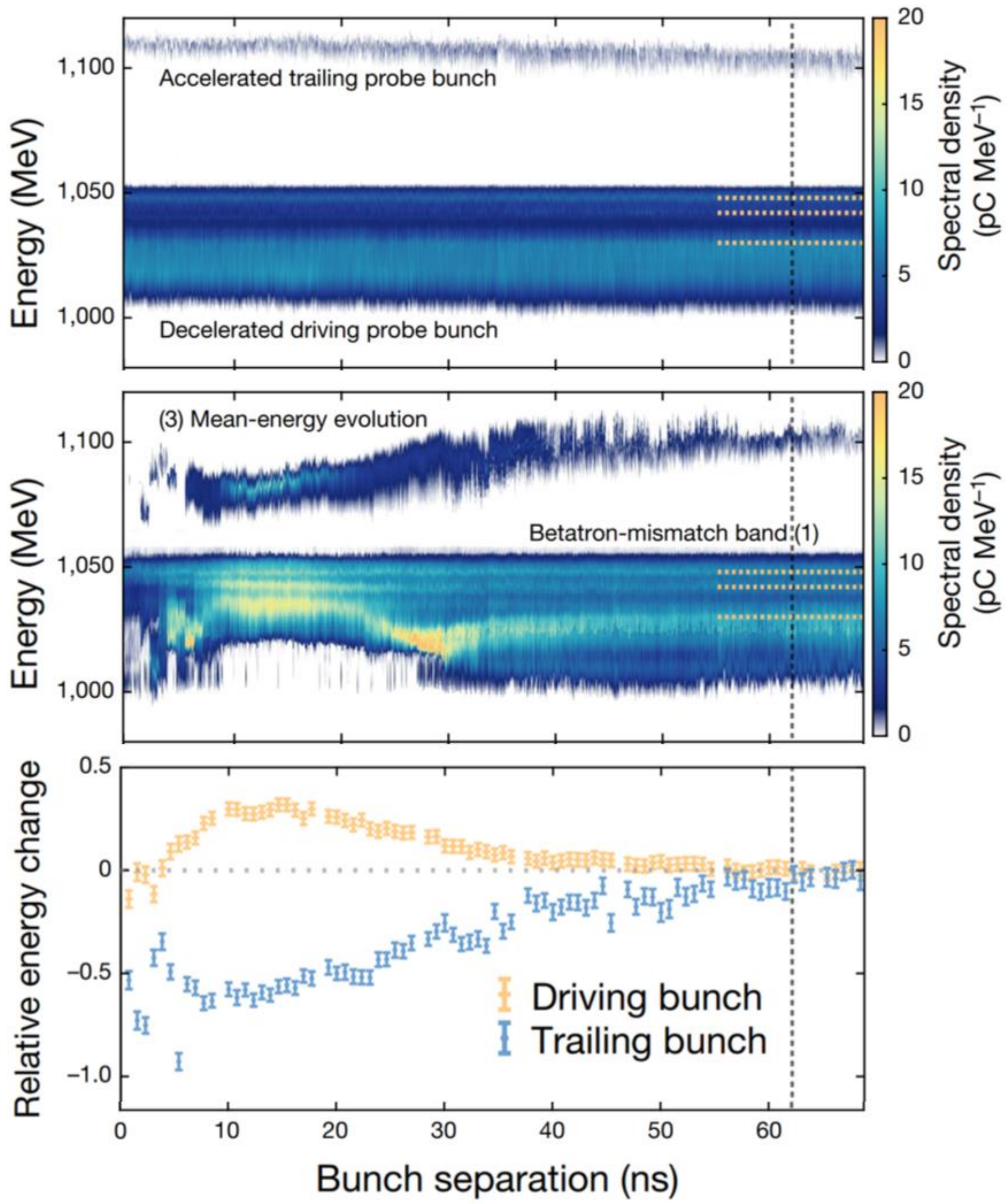
$$\frac{E_{gain/loss}^{pert} - E_{gain/loss}^{unpert}}{E_{gain/loss}^{unpert}}$$

$$t_{recovery} = 63\ ns$$

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# Long-term Ion Motion Dependencies

## Key parameters that could influence ion motion recovery timescale

| | |
|---|---|
| Wakefield strength | Plasma wave ponderomotive force on ions[6]. |
| Plasma density | Bunch-plasma coupling, plasma pressure gradient[8]. |
| Ionisation degree | Interactable material in the capillary[5]. |
| Temperature | Diffusion rate, ion acoustic wave velocity[8,9] $\rightarrow T^{-0.5}$. |
| Ion mass | Diffusion rate, ion acoustic wave velocity[8,9] $\rightarrow m^{0.5}$. |

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


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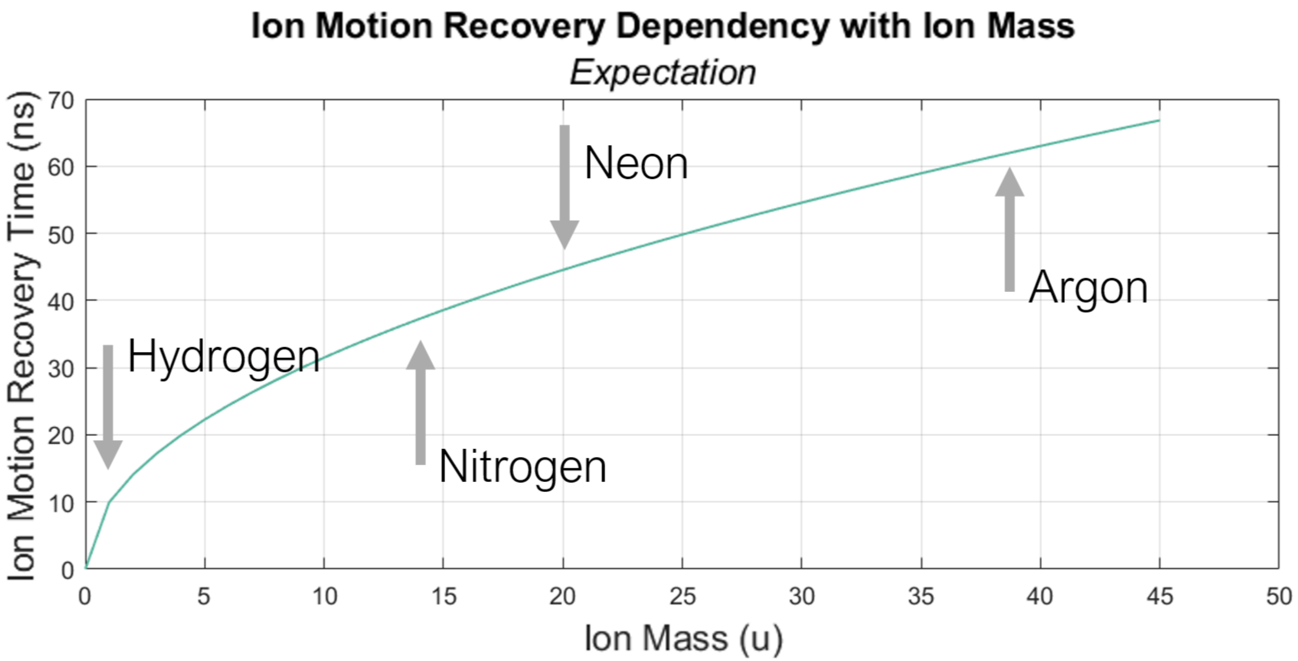
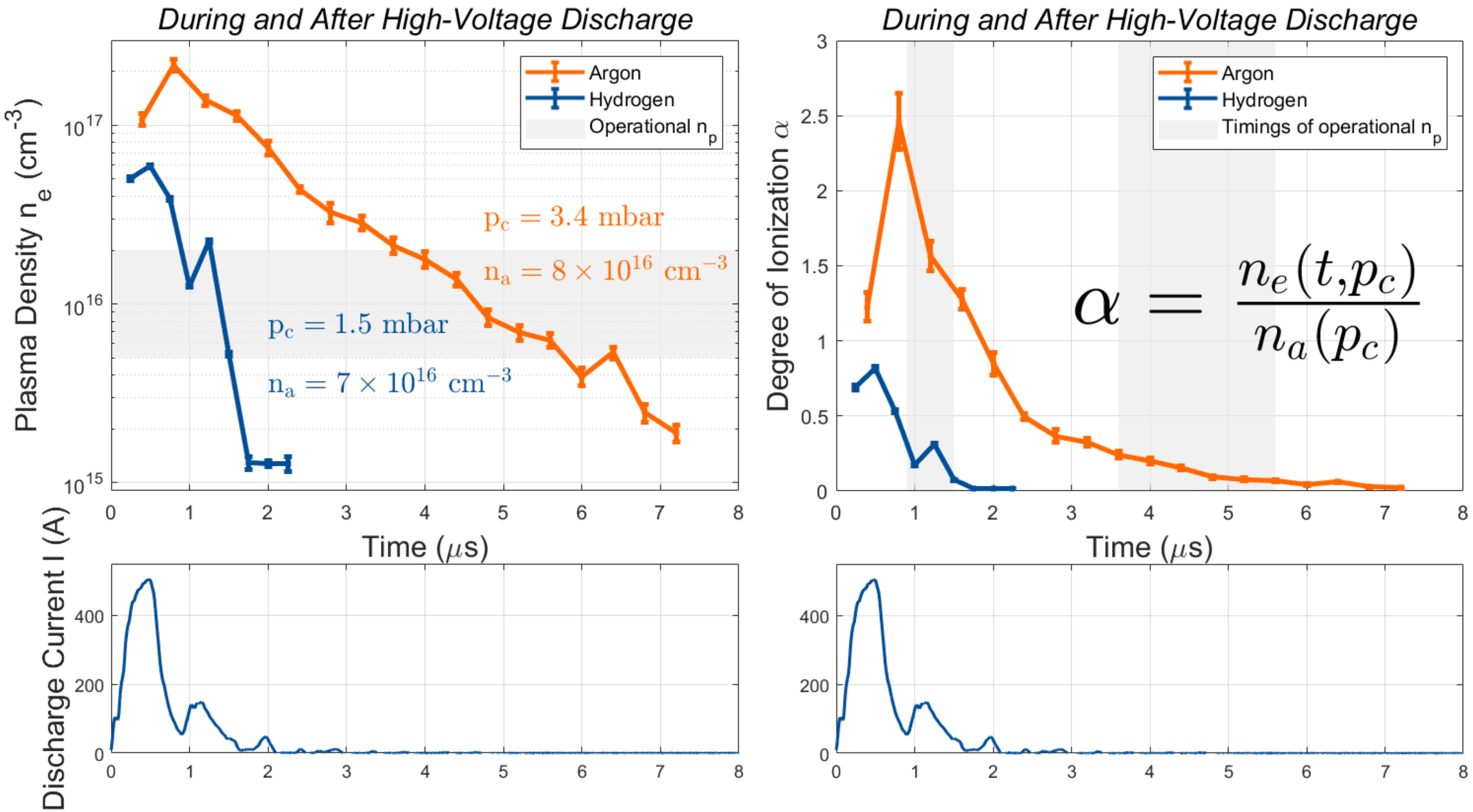
- Reduced ion mass → reduce the recovery time.
- Assumption: all other parameters stay the same.



# Plasma Characterisation

## Looking for equivalent recovery conditions in two different gases

- Optical Emission Spectroscopy (OES) [10].
- Estimation of $n_a$: gas supply system measurements and simulations.

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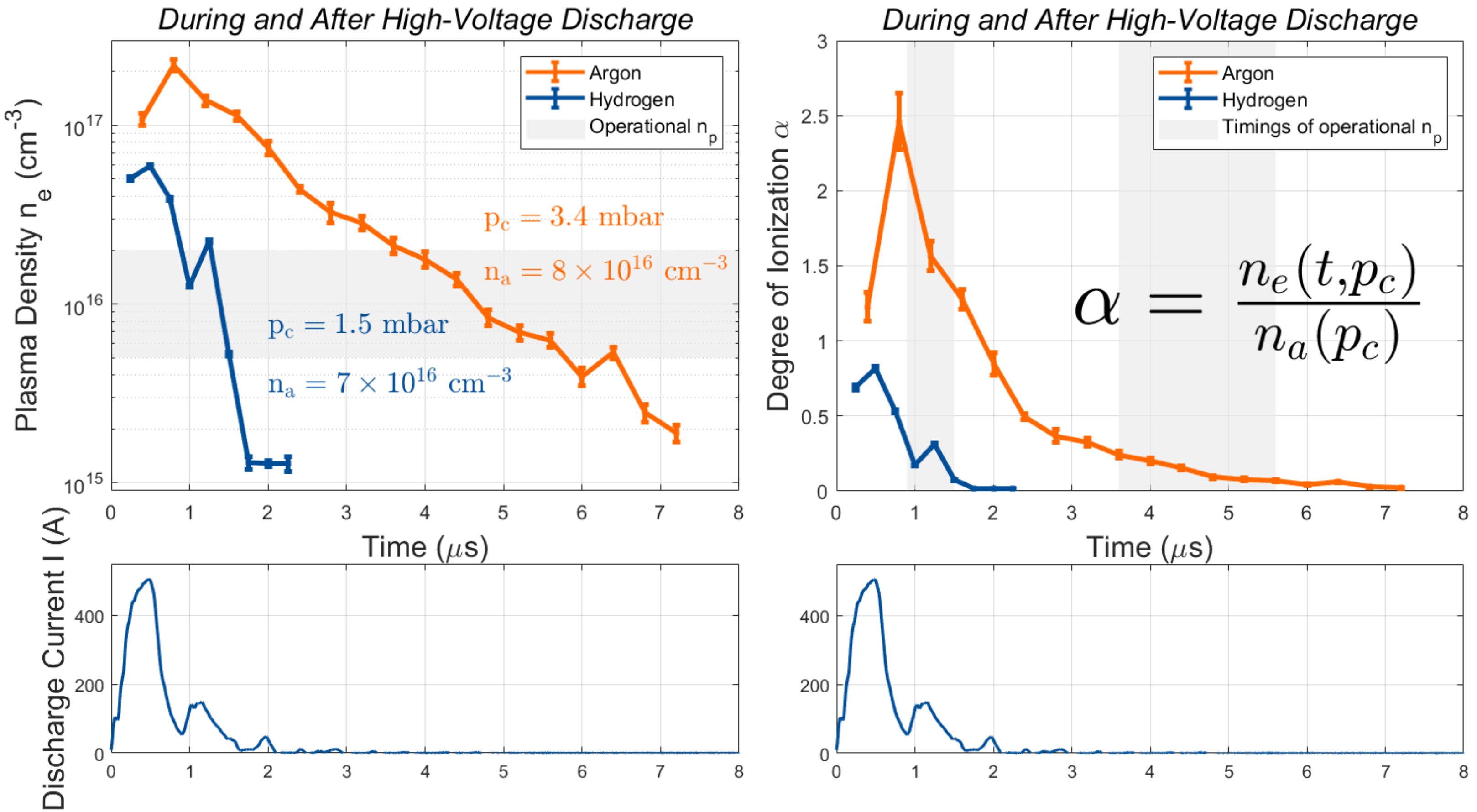


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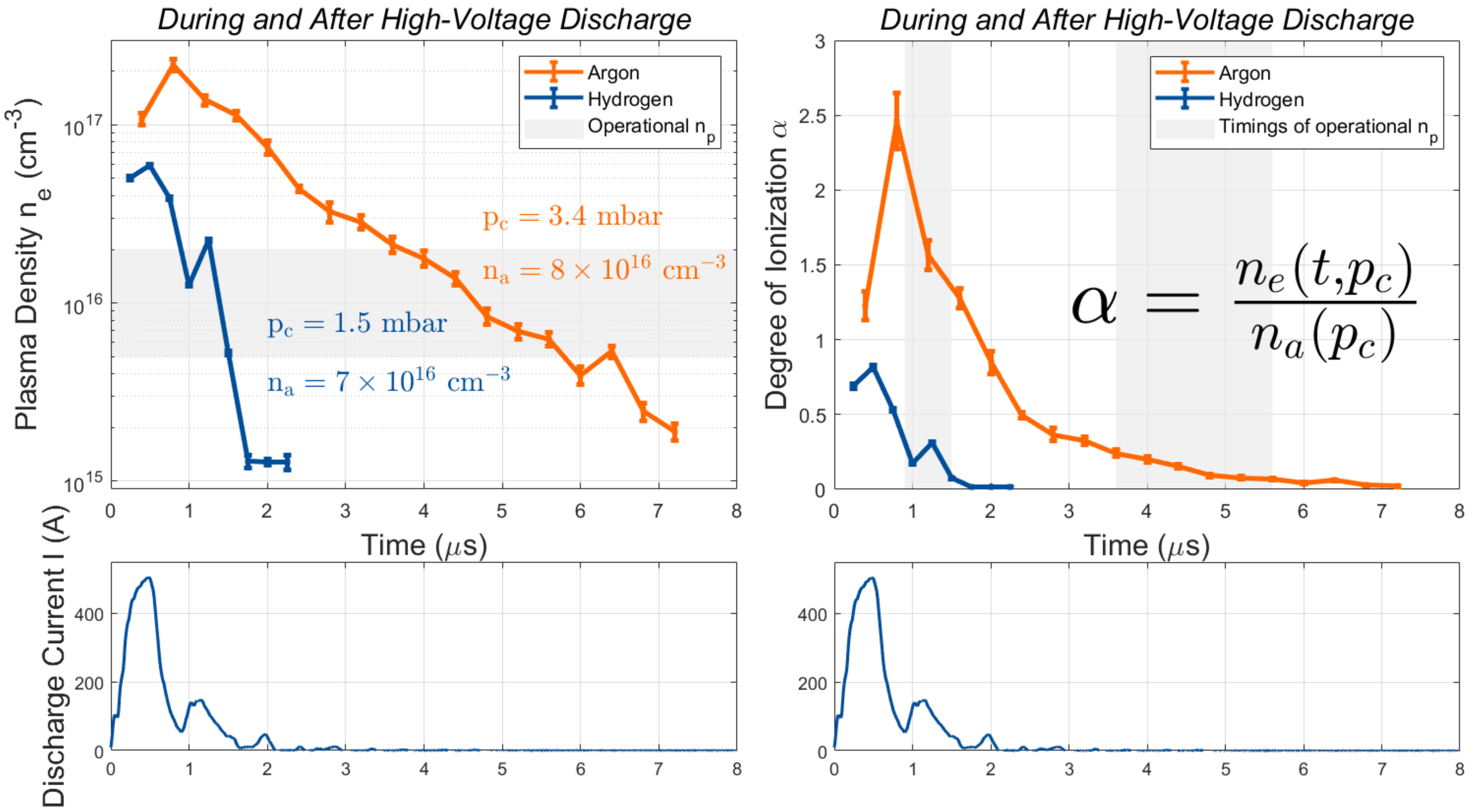
- Equivalent conditions (same $n_e$, $n_a$, $n_i$, $\alpha$) in $H_2$ and Ar occur under these assumptions:
  - The initial discharge-driven plasma and **gas expulsion** is similar for Ar and $H_2$ at their pressures,
  - Further post-discharge **atomic density is constant** and same for both.
  - Could be verified by MHD simulations of gas-capillary discharge.

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# Summary

- Plasma-wakefield acceleration: kHz - MHz-level repetition rate is needed.
- FLASHForward have measured a recovery time of O(100) ns in a plasma accelerator.
- A scaling estimation suggests that $\tau_{H_2} = $ O(10) ns.
- Long-term ion-motion recovery measurement: Argon vs Hydrogen.
- Need to understand $n_e$ and $\alpha$ evolution: OES plasma density measurements.
  - Different plasma settings in the capillary have been investigated.

# Status

- Beam-based measurements have been undertaken at FLASHForward; analysis ongoing.
- **Stay tuned: analysis and thesis wrap-up timescale O(1) year.**