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

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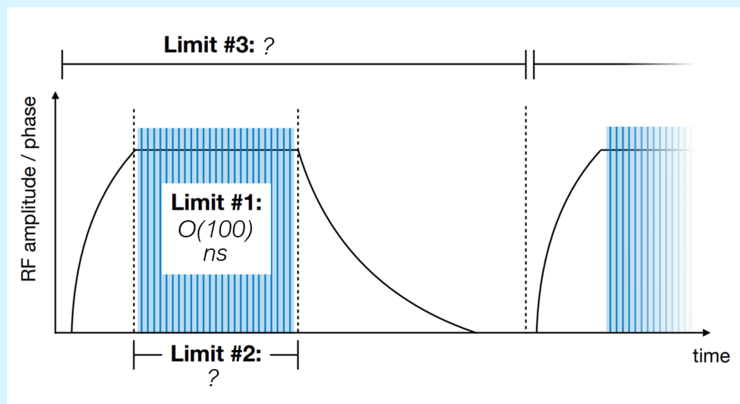
1. High-repetition-rate requirements

PWFA in future facilities

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

$$\mathcal{L} \propto f_{rep}$$
$$B_{int} \propto f_{rep}$$
$$f_{rep} = n_b f_p$$

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

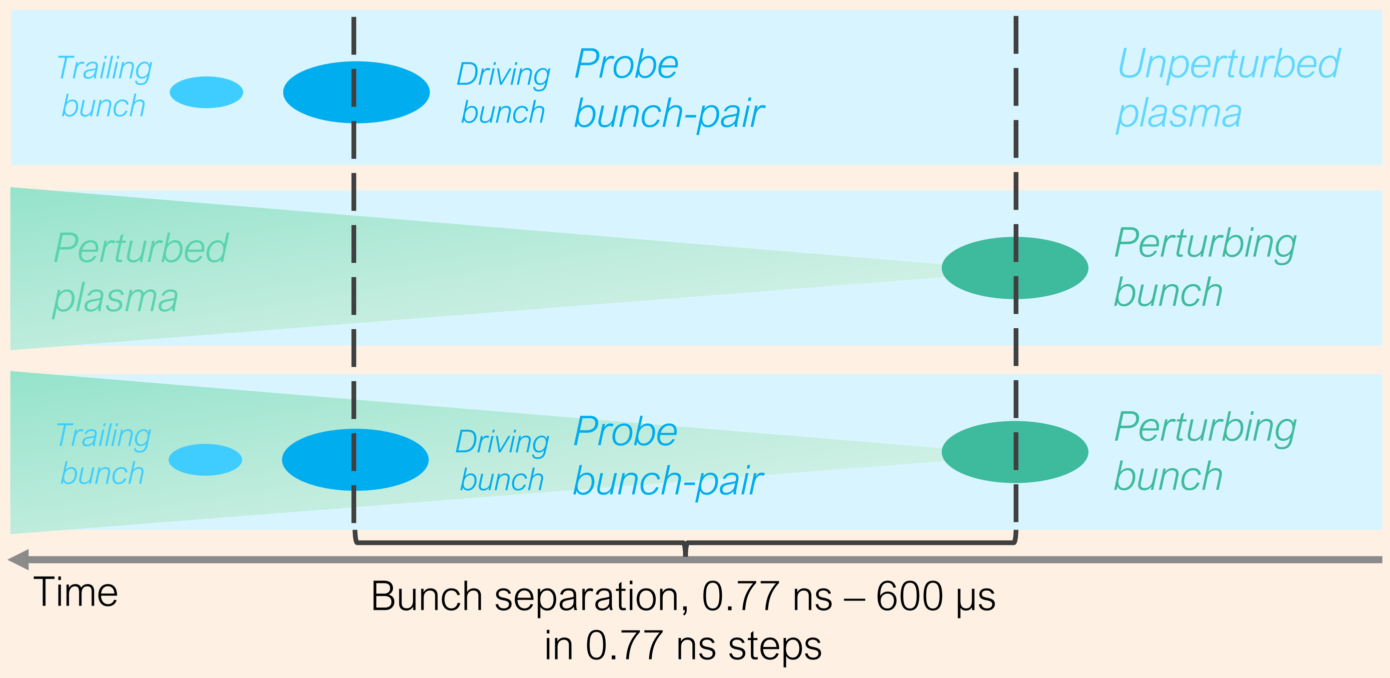


- Cumulative heating in plasma & infrastructure → Limit #2 and #3.
  - + required f_{rep} → Limit #1.
- If recovery time $\tau_{H_2} \sim 10$ ns:
  - Plasma is not a fundamental limit for repetition rate in future facilities.
  - Limit #1 O(10) ns.
  - Flexibility in bunch train shaping.

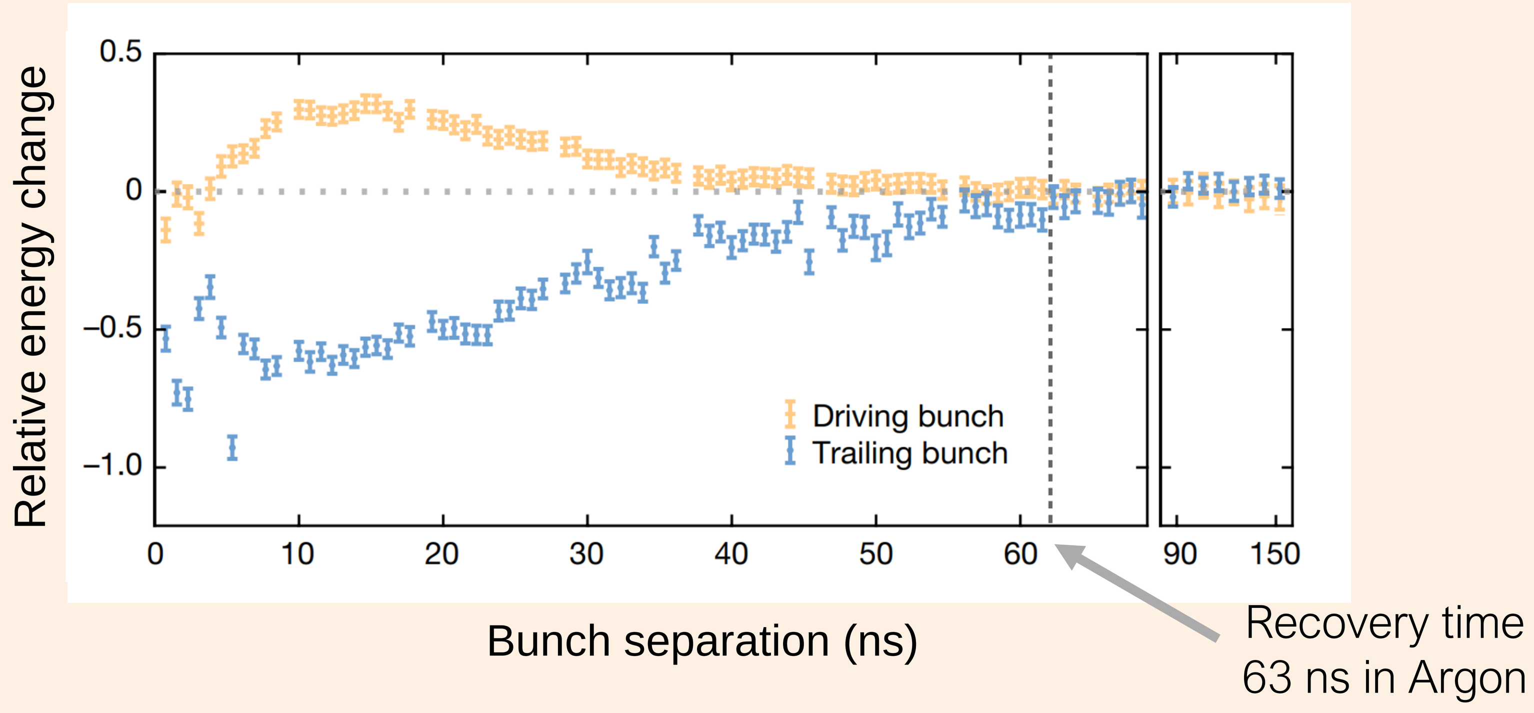
2. Measuring plasma recovery time

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[5,6,7].



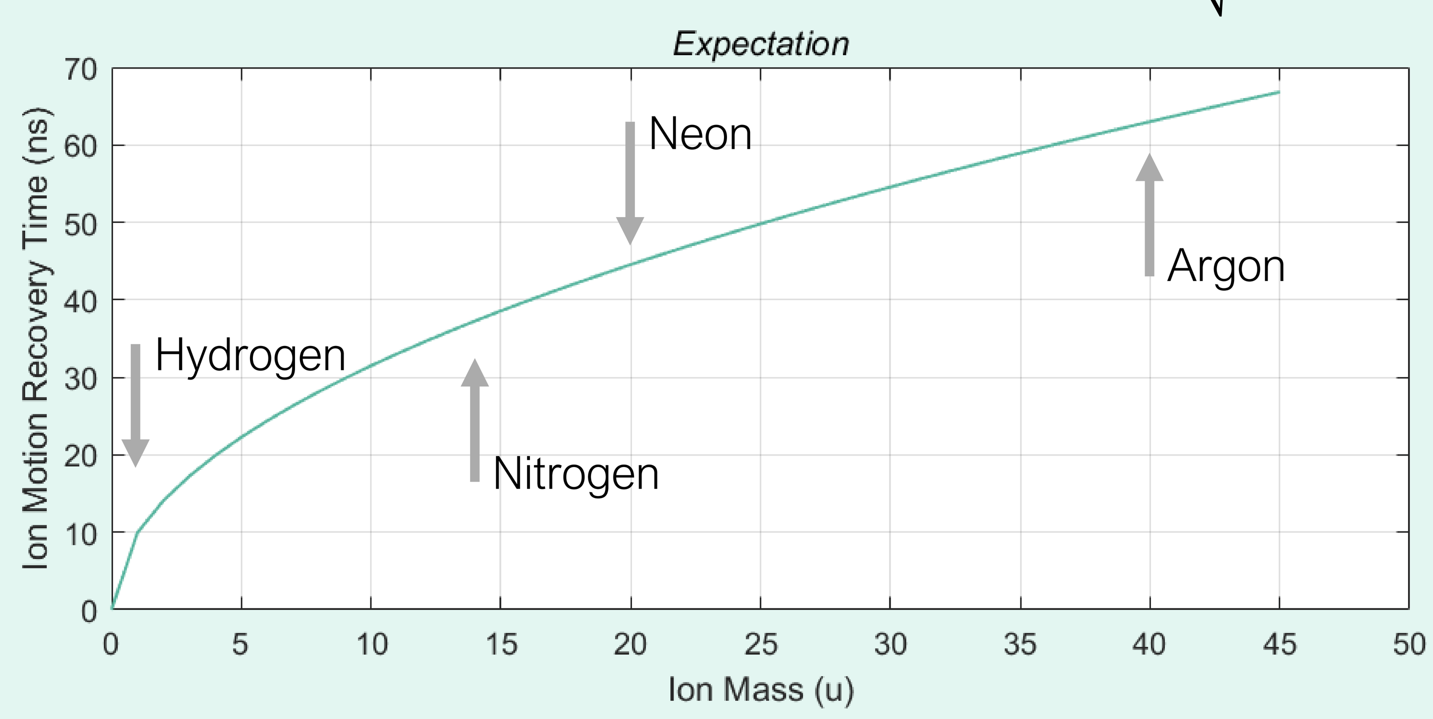
3. Long-term ion motion dependencies

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] → $T^{-0.5}$.
Ion mass	Diffusion rate, ion acoustic wave velocity[8,9] → $m^{0.5}$.

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

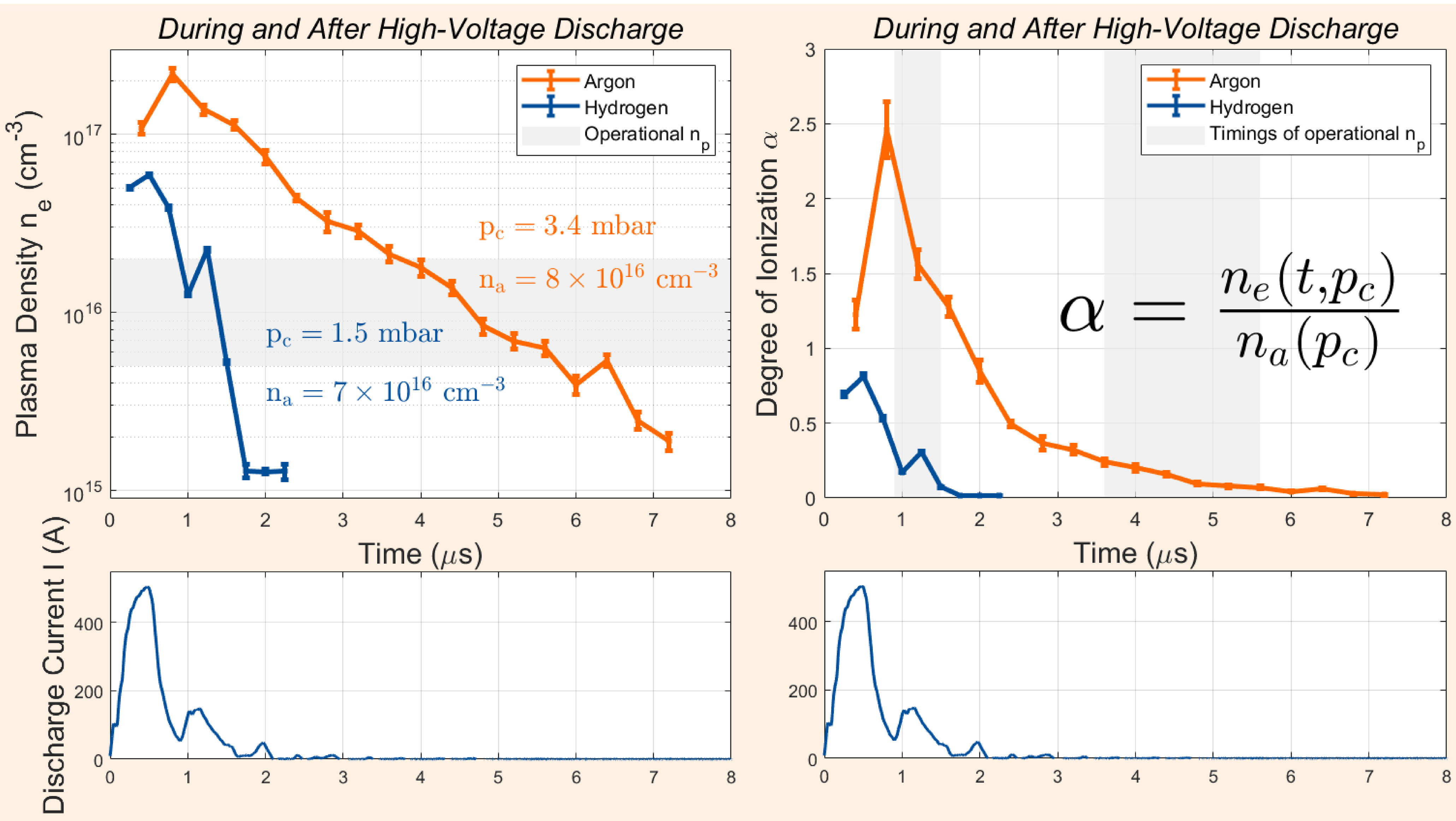
$$\tau_{H_2} = \tau_{Ar}\sqrt{\frac{m_{H_2}}{m_{Ar}}}$$



4. Plasma characterisation

Looking for equivalent recovery conditions in two different gases

- Similar plasma properties → **self-consistent ion-mass-dependent** recovery time comparison.
- Optical Emission Spectroscopy (OES) → find similar working points in Ar and H_2.
  - OES: Ar is doped with 3% H_2 → spectral H-alpha line broadening → **plasma density** value.[10]
- Estimation of n_a is based on gas supply system measurements and simulations.
  - $n_a = \frac{r_m p_c}{r_{pV} M}$, p_c – capillary pressure, r_m – mass flow rate, r_{pV} – flow rate, M – molecule mass.
- Equivalent conditions (same n_e, n_a, n_i, α) 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.
- The assumptions could be verified by MHD simulations of gas-capillary discharge.



5. Status

- FLASHForward: infrastructure to explore high-repetition-rate related dynamics in plasma:
  - Generating Hydrogen plasma,
  - FLASH electrons from GHz-double-bunches or MHz-bunch-trains.
- Different plasma settings in the capillary have been investigated.
- Characterised plasma needed for ion-mass-based recovery time reduction experiments.
- Beam-based measurements have been undertaken at FLASHForward; analysis ongoing.

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