A kHz length scalable plasma for the ALiVE proton driven plasma accelerator

7th European Advanced Accelerator Conference, Isola d'Elba, 24 Sep. 2025

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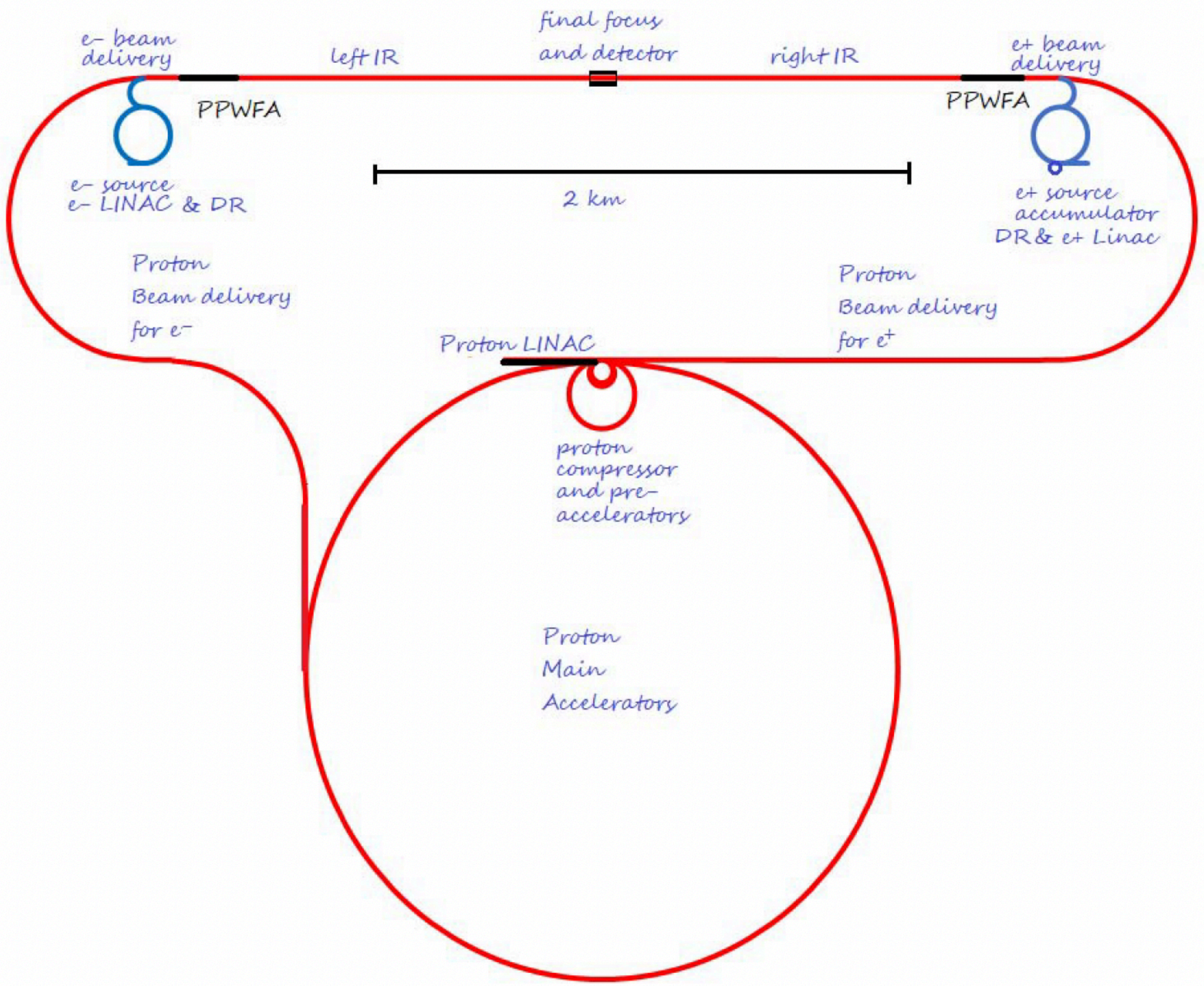
Grant: 2024.00263.CERN

ALiVE proposal



[1] J. P. Farmer, A. Caldwell and A. Pukhov, "Preliminary investigation of a Higgs factory based on proton-driven plasma wakefield acceleration", New J. Phys. 26, 113011 (2024).

[2] ALiVE Collaboration. "Proton-Driven Plasma Wakefield Acceleration for Future HEP Colliders." arXiv preprint arXiv:2503.21669 (2025), Input to the European Strategy for Particle Physics EPPS (2025)

Lepton collider for an Higgs factory and beyond

Single stage proton driven plasma accelerator

… AWAKE like, but

… Uses 500 GeV **short pulse** proton pulses

… **Single stage** proton driven plasma accelerator

… self-modulation not required

… < 0.2 % plasma density uniformity not required

… competitive luminosity with 10 - 20 kHz

Proton beam accelerated by FFAG rings

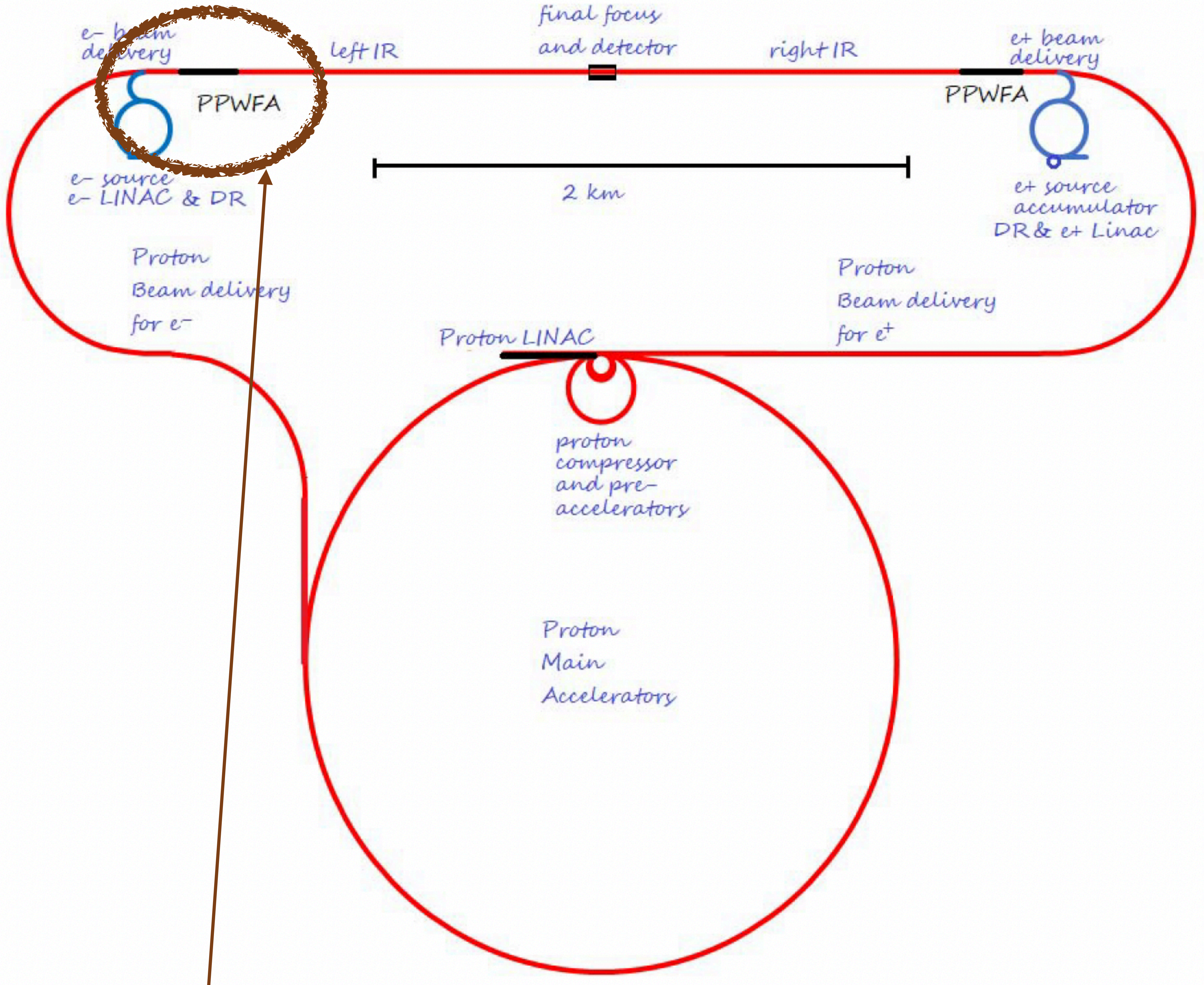
… Synchrotrons unlikely to reach required rep. rate

Seed 1 GeV short pulse electron beam

… single stage plasma acceleration towards > 300 GeV

Converging to using an RF accelerated positron beam

ALiVE proposal



This talk …

… A possible DPS plasma for the e- acceleration section

Lepton collider for an Higgs factory and beyond

Single stage proton driven plasma accelerator

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Seed 1 GeV short pulse electron beam

… single stage plasma acceleration towards > 300 GeV

Converging to using an RF accelerated positron beam

Background: AWAKE DPS

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AWAKE main requirements

Electron density

Range 1-10 $\times 10^{14}$ cm^{-3}

Uniformity/reproducibility/control < 0.2%

Ion mass

≥ Argon

Plasma length

From ~10 m to ~100 m at AWAKE

Discharge Plasma Source (DPS)

Ignition (High Voltage) + Heating (High Current)

Heating pulse ~500 A, ~10 μs (l=10m, ϕ=25 mm)

Length scalability

Plasma sections w/ 5-20 m w/common electrodes & magnetic current balancing

N. C. Lopes[1], C. Amoedo[1,2], Z. Najmudin[3], J. F. Silva[1], A. Sublet[2], N. Torrado[1], C. Torres[3] and the AWAKE team

1 Instituto Superior Tecnico, Lisbon, 2 CERN, 3 Imperial College

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CERN - AWAKE May 23 experiment

DPS Technology program

N. Torrado et al. IEEE Trans Plasma Sci. 51, 3619 (2023)

> 21 k plasmas made w/ length 3.5, 6.5 and 10 m

(single and double plasmas w/ common cathode)

Three gases He, Ar, Xe: density 0.01- 3.0x 10^{15} cm^{-3} (Xe) - 0.01- 0.5 x 10^{15} cm^{-3} (He)

Science program

Proton beam self modulation - verified in all AWAKE plasma densities

Ion mass effect - ion motion increasing for Xe, Ar and He plasmas

M. Turner et al., PRL 134, 155001 (2025)

Beam filamentation at highest densities

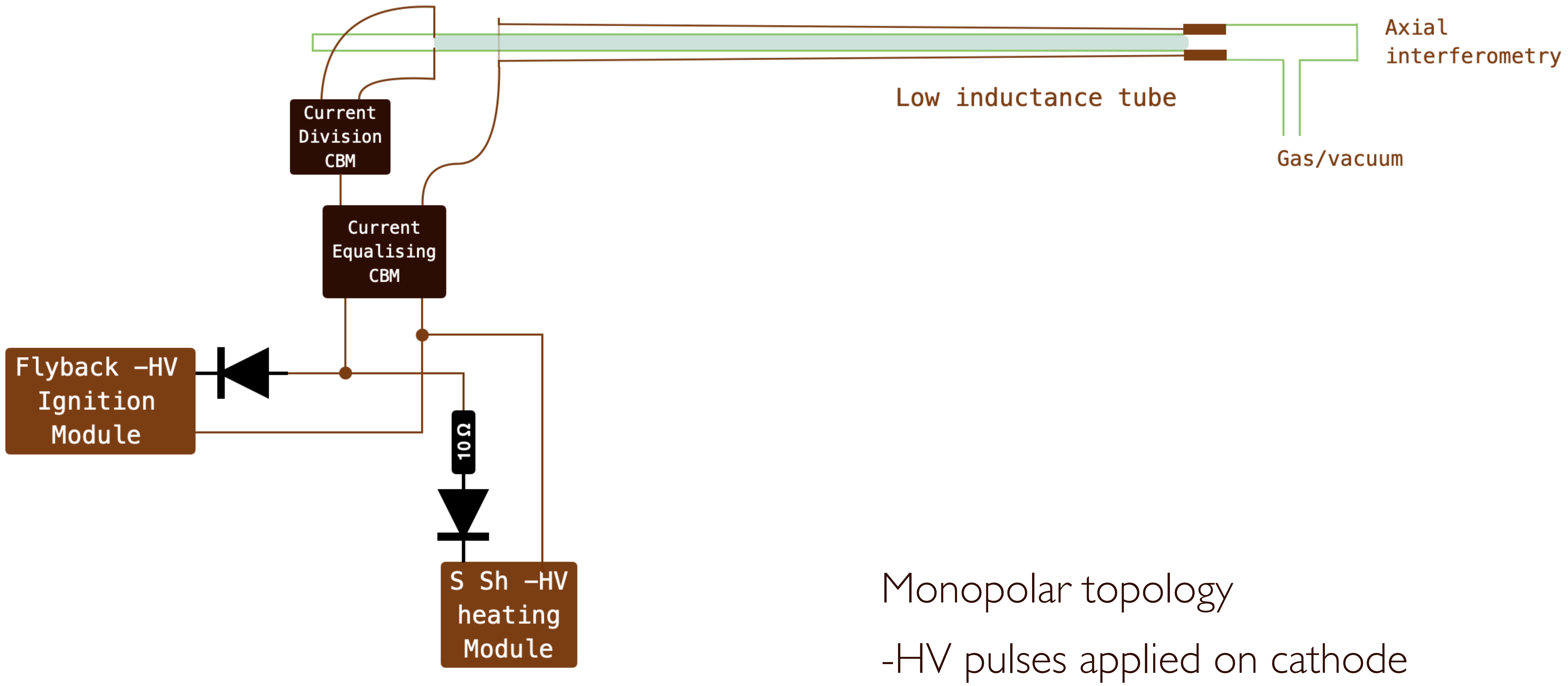
L. Verra et al., PRE 109, 055203 (2024)

Wakefield plasma-light

AWAKE DPS → ALiVE DPS (AWAKE monopolar single plasma)

Key issues	AWAKE
Plasma	
Density	1 - 10 x 10^{14} cm^{-3}
Repetition rate	< 0.1 Hz
Ions	≥ Argon
Ionisation fraction	~ 10 - 60 %
Plasma section length	5 - 20 m
n_e uniformity/ reproduc.	< 0.2 %
Support hardware	
Electrical	Inductive ignition + capacitive heating
Discharge/pulse topology	Cage monopolar
Vessel	Glass/Quartz ϕ~25 mm
Temperature/colling	Precise forcing 0.1%
Gas renewal	Beam aperture leaks/ sealed tube

In progress



Monopolar topology

-HV pulses applied on cathode

(currents always in same direction)

negligible gas flow in AWAKE

(τ_{pulse} < 50 μs & ~50 mHz)

AWAKE DPS → ALiVE DPS - 10 - 50 kHz repetition rate

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Key issues	AWAKE	ALiVE
Plasma		
Density	1 - 10 x 10^{14} cm^{-3}	3 - 10 x 10^{14} cm^{-3} ←
Repetition rate	< 0.1 Hz	10 - 50 kHz ←
Ions	≥ Argon	
Ionisation fraction	~ 10 - 60 %	
Plasma section length	5 - 20 m	
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Support hardware		
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Discharge/pulse topology	Cage monopolar	
Vessel	Glass/Quartz ϕ~25 mm	
Temperature/colling	Precise forcing 0.1%	
Gas renewal	Beam aperture leaks/ sealed tube	

Discharge heating energy

… for AWAKE Argon/Xenon 20-40% ionisation ~ 40 J / 5m

… estimation for 70 / 95 % ionisation ~ 200 J /5m

Extrapolation for 2 x more efficient 1 km plasma ~ 10 kJ

… 10 - 50 kHz lead to ~ **100 - 500 MW**

Possible **efficiency** improvements

… Noble gases (12.1 - 24.6 eV) → **Alkali vapours** (3.9 - 5.4 eV)

… Radial plasma confinement with **solenoid magnetic field**

… High(er) voltage and **shorter pulses**

AWAKE DPS → ALiVE DPS - 10 - 50 kHz repetition rate

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Key issues	AWAKE	ALiVE
Plasma		
Density	1 - 10 x 10^{14} cm^{-3}	3 - 10 x 10^{14} cm^{-3} ←
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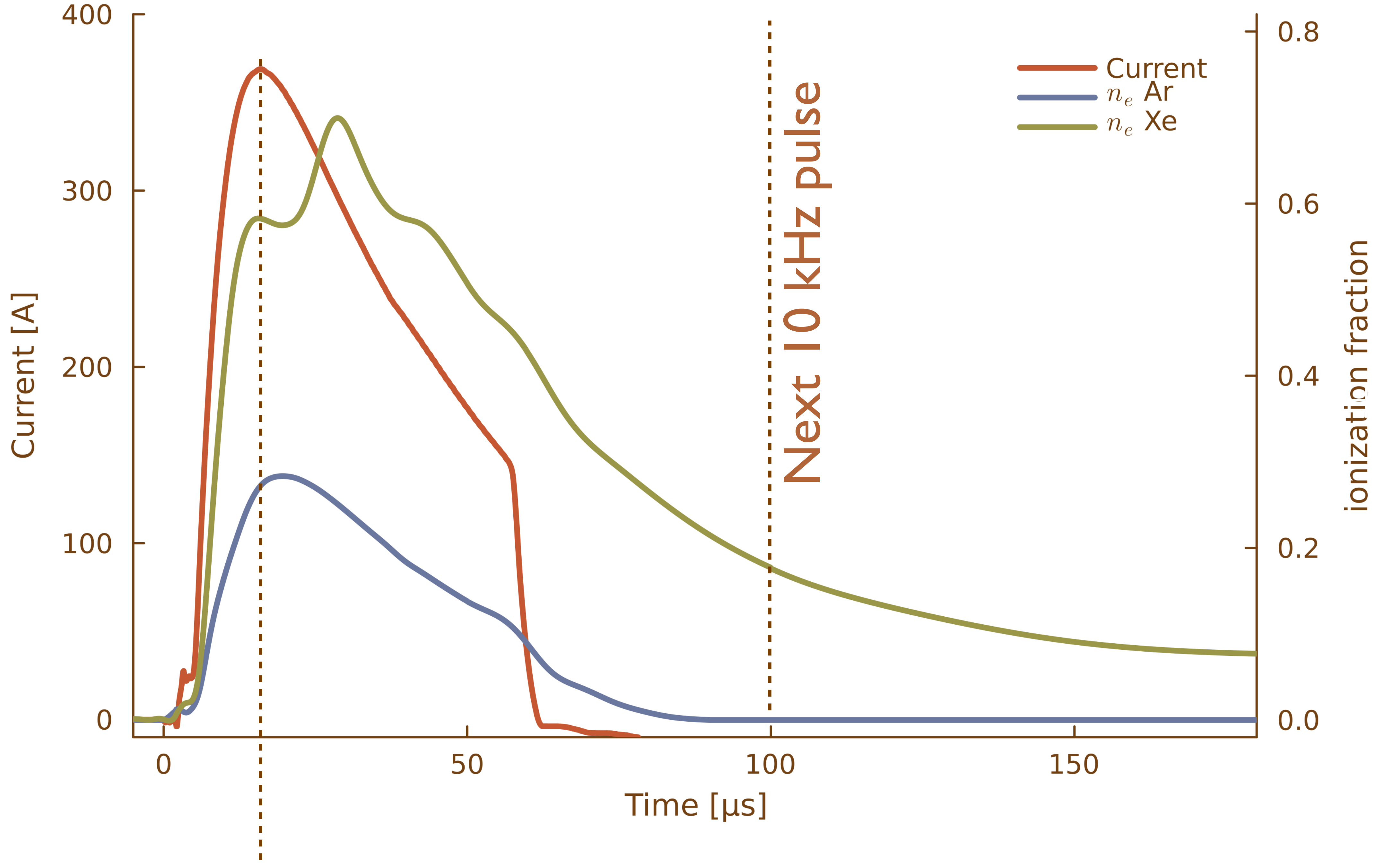
Gas renewal	Beam aperture leaks/ sealed tube	

Typical DPS plasma density at $n_e = 5 \times 10^{14} cm^{-3}$



5-20 µs - current peak delay

Faster discharge required

… 50% inductance reduction

… 100% voltage increase

Aiming ~ 1 µs pulses (Si IGBT's → SIC MOSFETs)

AWAKE DPS → ALiVE DPS - Ion motion

Key issues	ALiVE
Plasma	
Density	3 - 10 x 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
Ions	Z ≥ Ne / Na (Ar / K) ←
Ionisation fraction	
Plasma section length	
n_e uniformity/ reproduc.	
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	

Ion motion caused by witness e-bunch may move light ions towards the bunch axis degrading the emittance…

For **$N_{e\ bunch}$ = 1 - 2 x10^{10},** σz = 75 μm, σr = 0.25 μm (after adiabatic compression)
… Ions move ∼ 1 - 2 μm / M_i (u) in $\tau = \sigma_z / c$ = 250 fs

To limit motion to ∼ $\sigma_r/5$ = 50 nm …
… we need **M_i > 18 - 36 ∼ Ne / Na - Ar / K**

Disclaimer
Precise simulations with for the effect of ion motion are required…
… effect strongly depend on beam shape evolution
… shorter electron beams are preferable since effect increases with σ_z

AWAKE DPS → ALiVE DPS - ~ 100% first ionisation required

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Key issues	ALiVE
Plasma	
Density	3 - 10 x 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
Ions	Z ≥ Ne / Na (Ar / K)
Ionisation fraction	~ 100% ←
Plasma section length	
n_e uniformity/ reproduc.	
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	

Discharge partial first ionisation

…lead to significant plasmas density increase after witness bunch distorting wakefield

~ 100% first ionisation…

… requires ≥ 1 kA heating current for Xe (Higher for lighter gases)

… not feasible at > 10 kHz

… plasma thermal loss to wall is the main problem

… Possible solution

… Alkali vapor (Na, K, Rb, Cs)

… mild plasma radial confinement (~ 0.2 - 0.5 T solenoid field, $\omega_c << \omega_{pe}$)

AWAKE DPS → ALiVE DPS - ~ Second (field) ionisation

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Key issues	ALiVE
Plasma	
Density	3 - 10 x 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
Ions	Z ≥ Ne / Na (Ar / K) ←
Ionisation fraction	~ 100%
Plasma section length	
n_e uniformity/ reproduc.	
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	

Second ionisation (tunnel ionisation) caused by intense witness e-bunch may distort wakefield…

AWAKE DPS → ALiVE DPS - Second ionisation

Key issues	ALiVE
Plasma	
Density	3 - 10 × 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
Ions	Z ≥ Ne / Na (Ar / K) ←
Ionisation fraction	~ 100%
Plasma section length	
n_e uniformity/ reproduc.	
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	

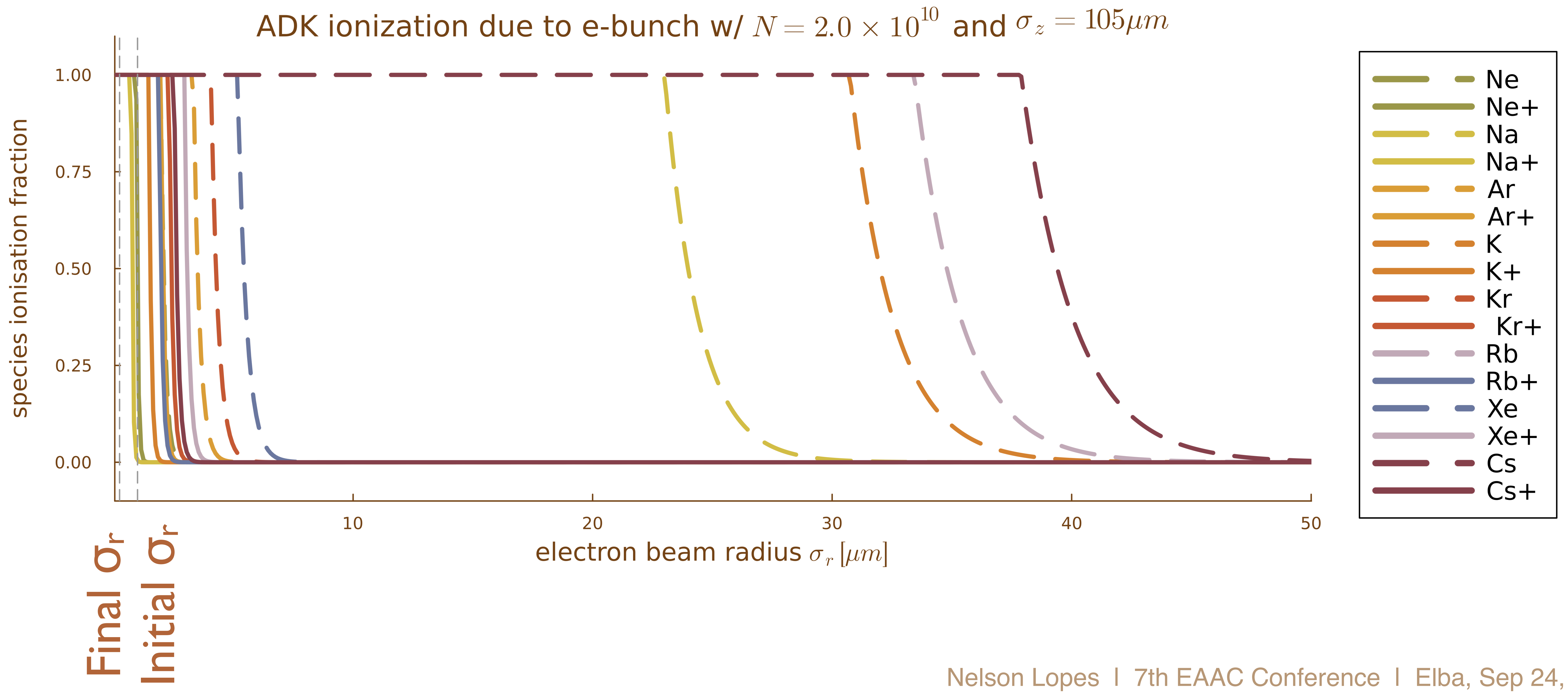
Second ionisation (tunnel ionisation) caused by intense witness e-bunch may distort wakefield…

Intense electron beam - adiabatic focusing during acceleration…

… from σr ~ 1 μm to σr ~ 0.25 μm

Beam E field may reach > 200 GV/m…

… second ionisation possible



AWAKE DPS → ALiVE DPS - Second ionisation

Key issues	ALiVE
Plasma	
Density	3 - 10 × 10^{14} cm^{-3}
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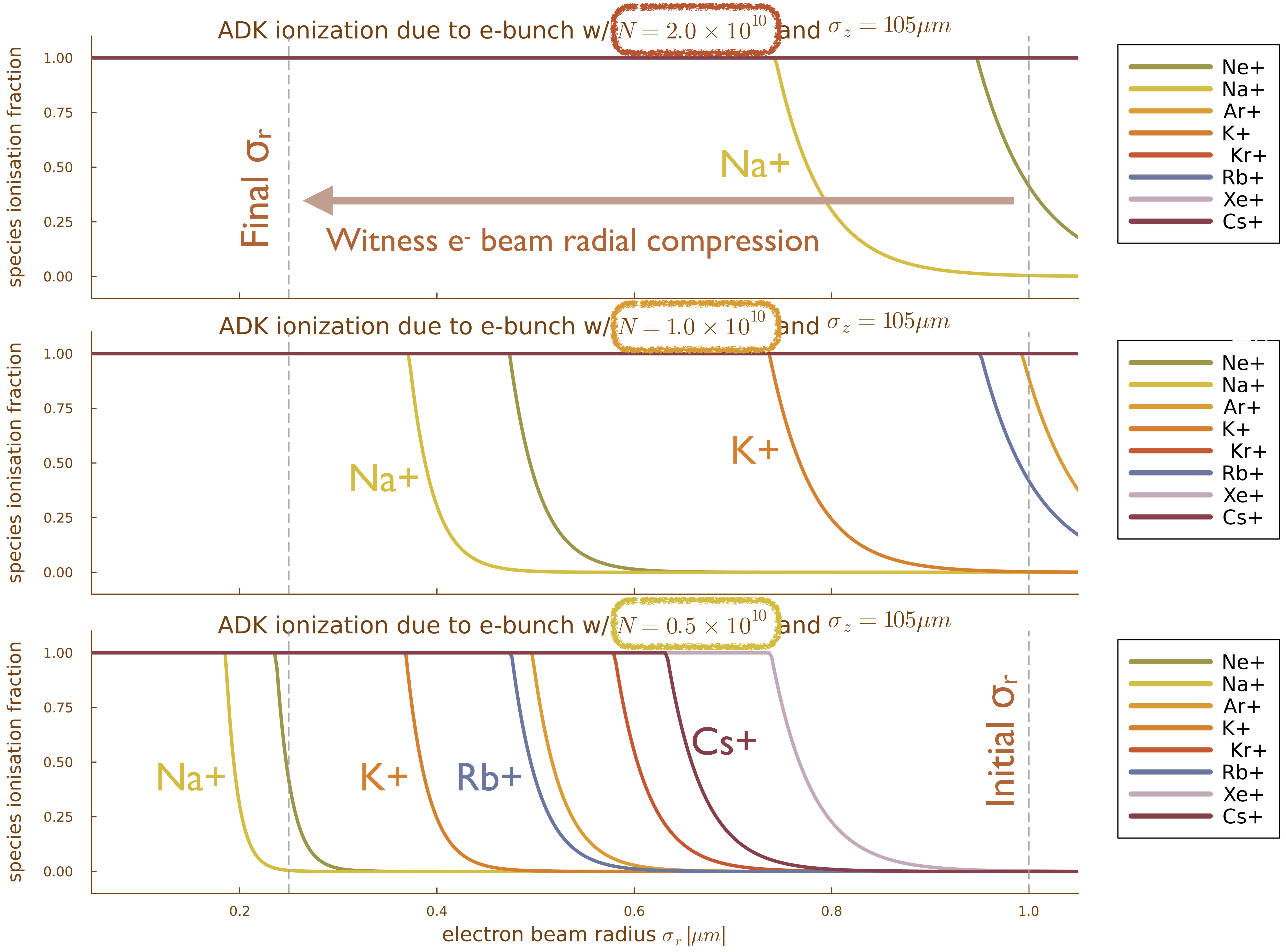
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	



AWAKE DPS → ALiVE DPS - Second ionisation

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Key issues	ALiVE
Plasma	
Density	3 - 10 x 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
Ions	Z = Na (K) ? ? ? ←
Ionisation fraction	~ 100%
Plasma section length	
n_e uniformity/ reproduc.	
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	

Second ionisation (tunnel ionisation) caused by intense witness e-bunch may distort wakefield…

Intense electron beam - adiabatic focusing during acceleration…

… from σ_r ~ 1 μm to σ_r ~ 0.25 μm

Beam E field may reach > 200 GV/m…

… second ionisation possible

Most adequate ion… likely **Na** but…

Second ionisation may require project adjustments…

… **plasma density** (lower plasma density reduces witness beam focusing)

… witness **bunch charge** (lower charge reduces ion motion and second ionisation)

… witness **bunch length**

… **repetition rate** increase to compensate for other adjustment (conserving target luminosity)

Disclaimer

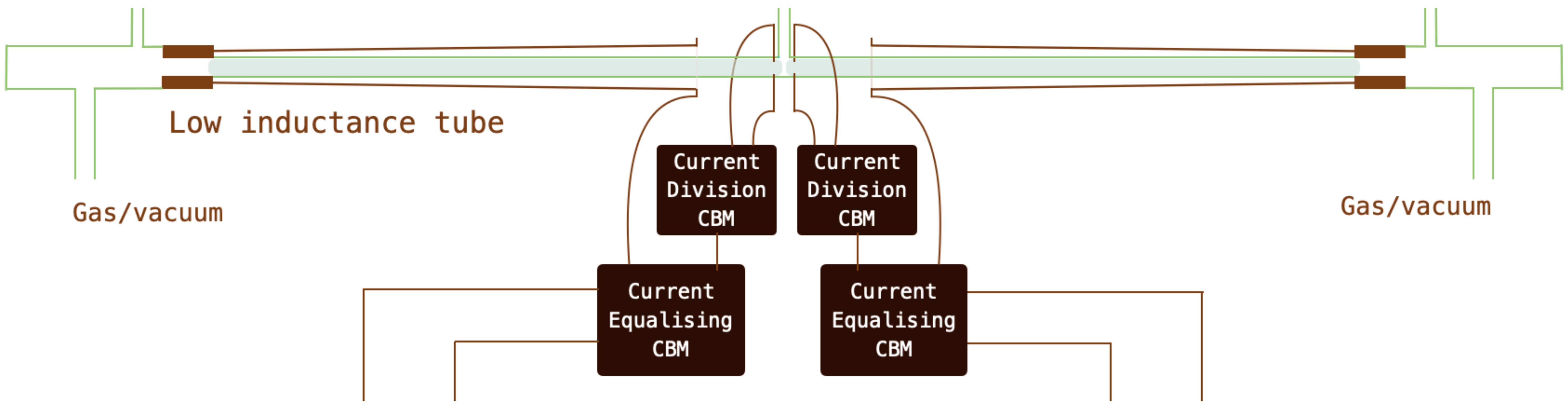
Precise simulations with the effect of ion motion and second ionization are required…

… effect strongly depend on beam shape evolution

AWAKE DPS → ALiVE DPS - plasma length

Key issues	ALiVE
Plasma	
Density	3 - 10 x 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
Ions	Z = Na (K) ? ? ?
Ionisation fraction	~ 100%
Plasma section length	2x10 m modules (>240m) ←
n_e uniformity/ reproduc.	
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	

Plasma modules



Tube inductance limits repetition rate

… in AWAKE a 5 m long tube as L_{tube} ~ 60 μH … (400 A) rise time ~ 5 μs

… ALiVE aims for ≤ 1 μs rise time

… optimised low inductance topology **10 m , 40 μH**

… higher heating voltage (+ pulse shaping) 12 kV

… lower heating current with Alkalis and B (< 200 A)

… **(200 A) rise time ~ 0.7 μs**

AWAKE DPS → ALiVE DPS - plasma density uniformity

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Key issues	ALiVE
Plasma	
Density	3 - 10 x 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
Ions	Z = Na (K) ? ? ?
Ionisation fraction	~ 100%
Plasma section length	2x10 m modules (>240m)
n_e uniformity/ reproduc.	Not critical… ←
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	

Short pulse proton driver…

Proton pulse duration ~ matched to plasma period

Unlike AWAKE self-modulated long pulse (→ < 0.2% uniformity requirement)

Plasma density uniformity flexibility …

… useful for length scaling

AWAKE DPS → ALiVE DPS - Constrains on electrical circuit

Key issues	ALiVE
Plasma	
Density	3 - 10 x 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
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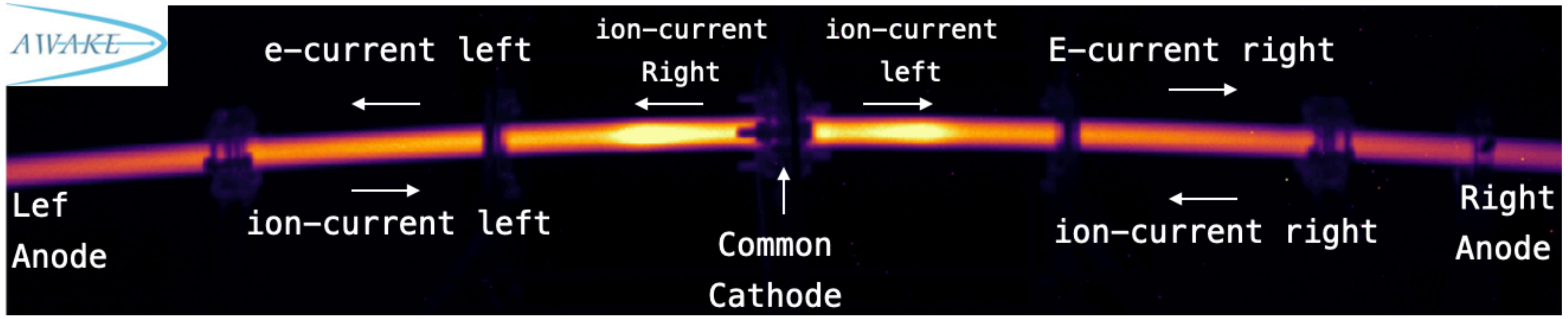
Plasma section length	2x10 m modules (>240m)
n_e uniformity/ reproduc.	Not critical…
Support hardware	
Electrical	
Discharge/pulse topology	
Vessel	
Temperature/colling	
Gas renewal	

Plasma recombination incomplete (before next pulse)

Continuous plasmas may self-modulate (for our parameters) →

Net ion drift (due to high duty cycle)

Ions accelerate against electron current ↓

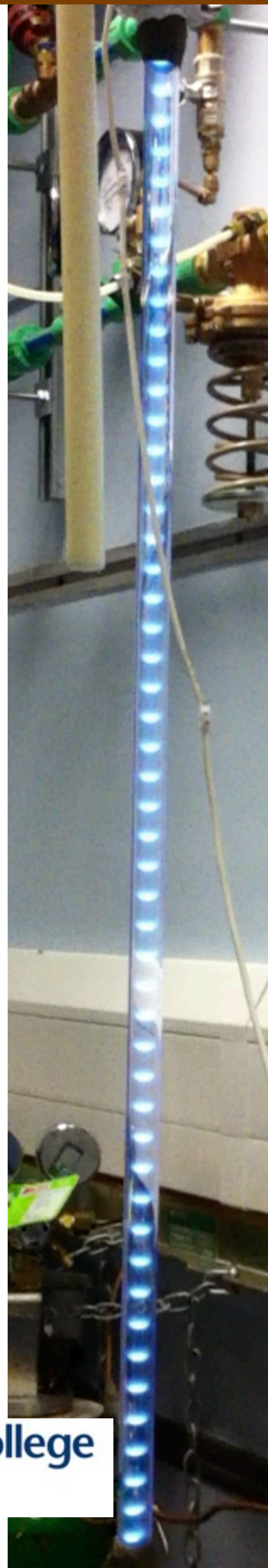


←

Single shot plasma in AWAKE (~ 500 μs after current pulse)
(Tunnel picture with vignetting … the tube is straight !)

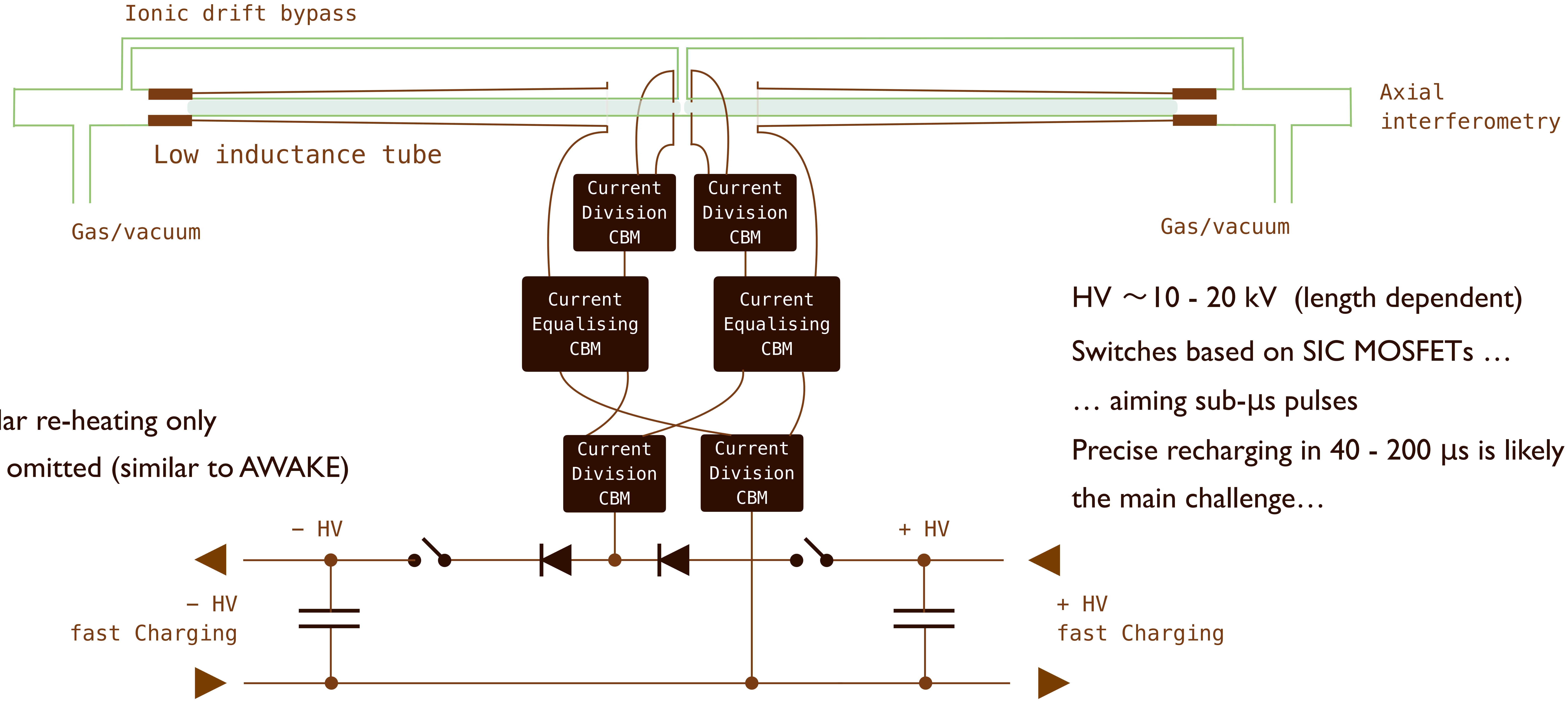
Ok for AWAKE, but unacceptable for >10 KHz ALiVE

Solution: DPS monopolar → DPS bipolar topology



Imperial College London

AWAKE DPS → ALiVE DPS - Constrains on electrical circuit



Scheme

with bipolar re-heating only

Ignition is omitted (similar to AWAKE)

HV ~10 - 20 kV (length dependent)

Switches based on SIC MOSFETs …

… aiming sub-μs pulses

Precise recharging in 40 - 200 μs is likely the main challenge…

AWAKE DPS → ALiVE DPS - Constrains on electrical circuit

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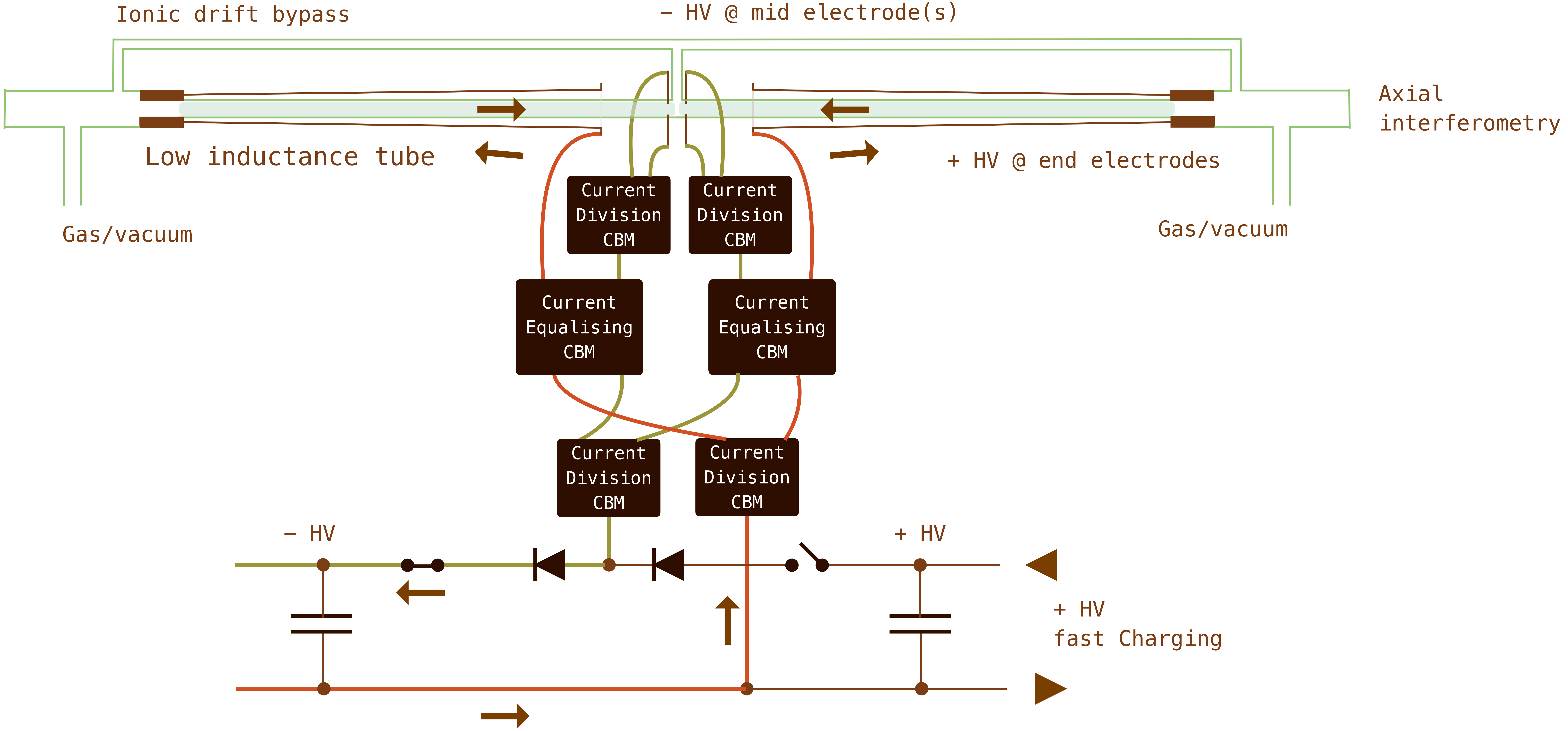
Bipolar - Odd discharges



AWAKE DPS → ALiVE DPS - Constrains on electrical circuit

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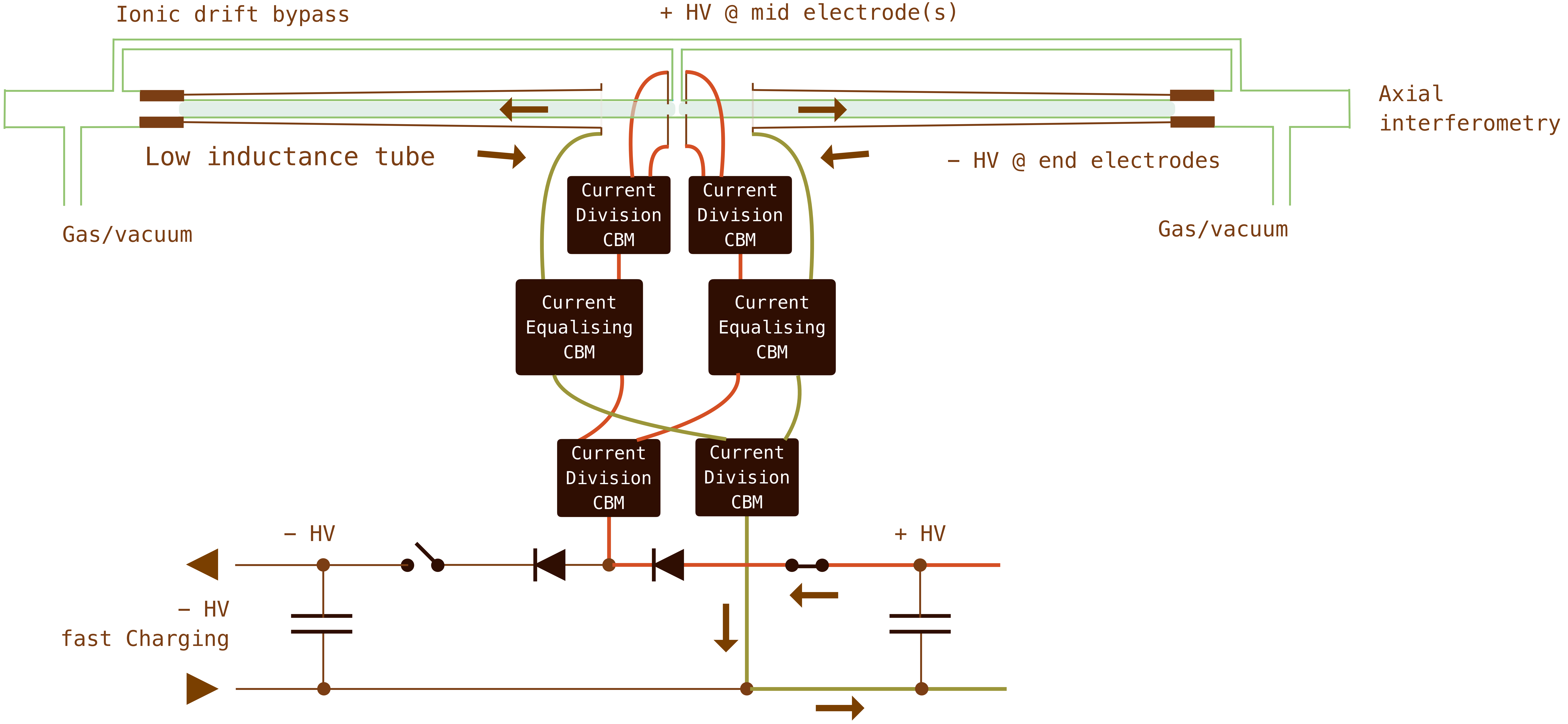
Bipolar - Even discharges



AWAKE DPS → ALiVE DPS - Alkali vapours discharge vessel

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Key issues	ALiVE
Plasma	
Density	3 - 10 x 10^{14} cm^{-3}
Repetition rate	10 - 50 kHz
Ions	Z = Na (K) ? ? ?
Ionisation fraction	~ 100%
Plasma section length	2x10 m modules (>240m)
n_e uniformity/ reproduc.	Not critical…
Support hardware	
Electrical	Inductive ignition +
	Capacitive HF re-heating
Discharge/pulse topology	2 plasma cage bipolar
Vessel	←
Temperature/colling	
Gas renewal	

On a DPS … plasma uniformity dependent on…

… tube diameter uniformity

… tube temperature uniformity

…

Alkali temperatures for n_0 = 1 - 10 e^{14} cm^{-3} * - 140 - 350 °C

Atom/Ion	1e14 cm⁻³		5e14 cm⁻³		10e14 cm⁻³	
	temperature [°C]	Pressure [Pa]	temperature [°C]	Pressure [Pa]	temperature [°C]	Pressure [Pa]
Na	273.8	0.757	317.7	4.08	339.2	8.49
K	190.7	0.642	229.0	3.47	247.7	7.21
Rb	149.9	0.586	185.0	3.16	202.2	6.59
Cs	133.4	0.562	167.7	3.04	184.5	6.34

* www.tuwien.at/en/phy/iap/tools/vapor-pressure-calculator … ±10% error

AWAKE DPS → ALiVE DPS - Alkali vapours discharge vessel

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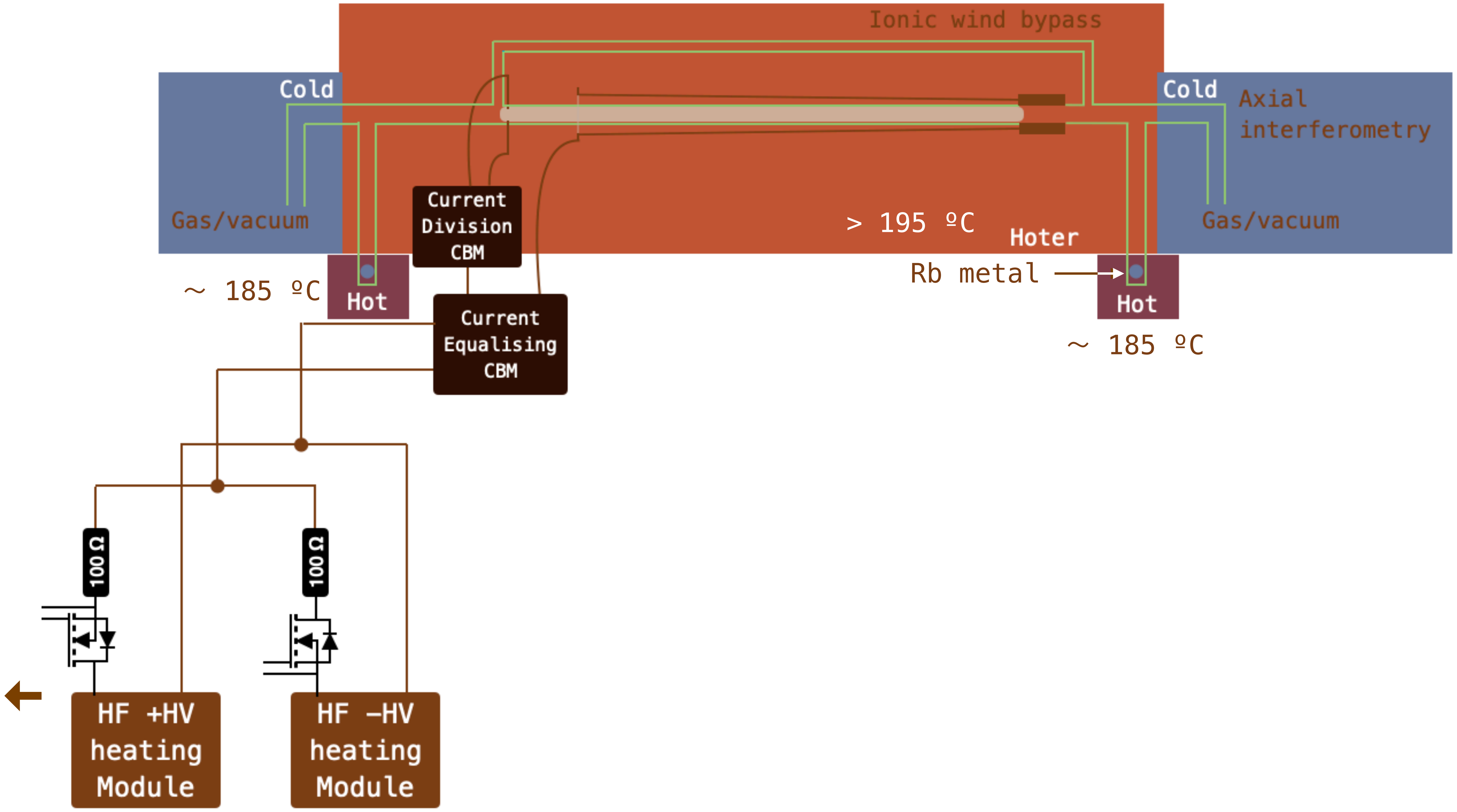
Ions	Z = Na (K) ? ? ?
Ionisation fraction	~ 100%
Plasma section length	2x10 m modules (>240m)
n_e uniformity/ reproduc.	Not critical…
Support hardware	
Electrical	Inductive ignition + Capacitive HF re-heating
Discharge/pulse topology	2 plasma cage bipolar
Vessel	Ceramic / glass / quartz
Temperature/colling	140 -350 ºC precision heat
Gas renewal	N A

Simplified scheme for a demo Rubidium HF bipolar DPS up to n_0 = 5 x 10^{14} cm^{-3}



ALiVE DPS - development and feasibility demonstration

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0 Precise simulations to establish safe plasma parameters - Ion motion and ionisation effects - **what plasma species are allowed ?**

1 **Alkali DPS, single-shot, transparent tube, Rubidium/Potassium - infere Alkali plasma uniformity (2026-7)**

2 **DPS with pulsed solenoid B field, noble gases - full first ionisation** (in progress / preliminary results)

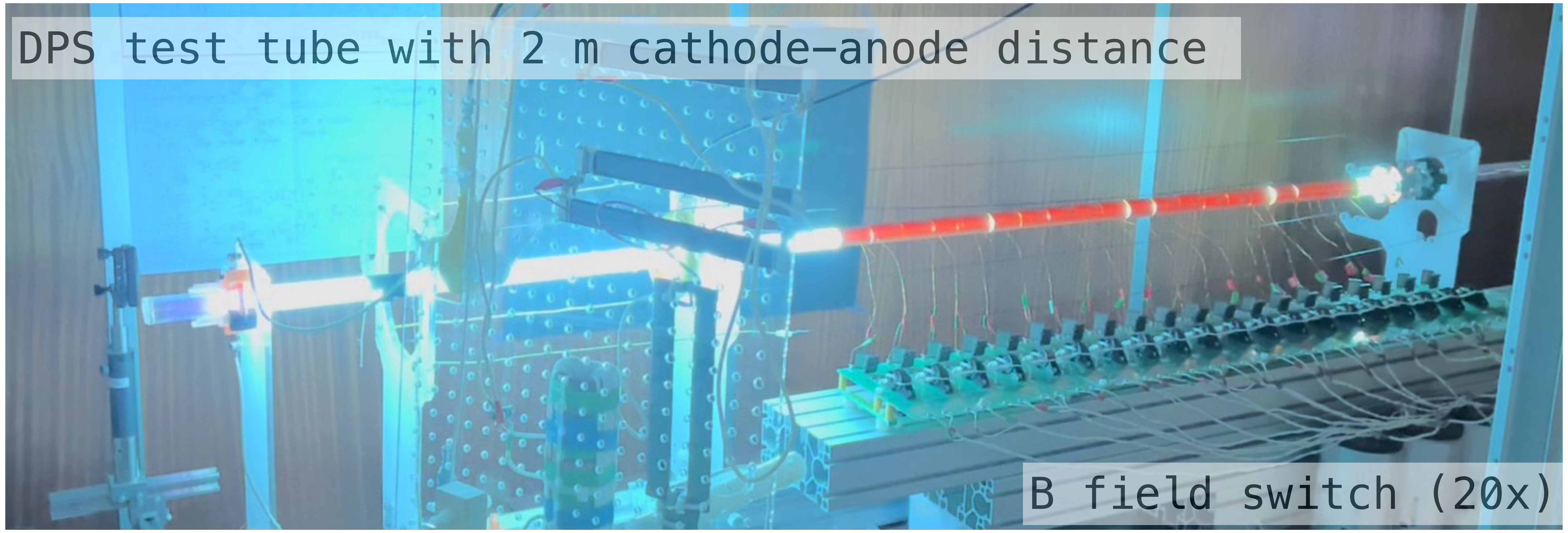
3 **HF - DPS with pulsed solenoid B field, noble gases, - feasibility of bipolar HF electric circuit (2026-7)**

4 HF - DPS with pulsed solenoid B field, Rubidium - alkali HF plasma uniformity (> 2027)

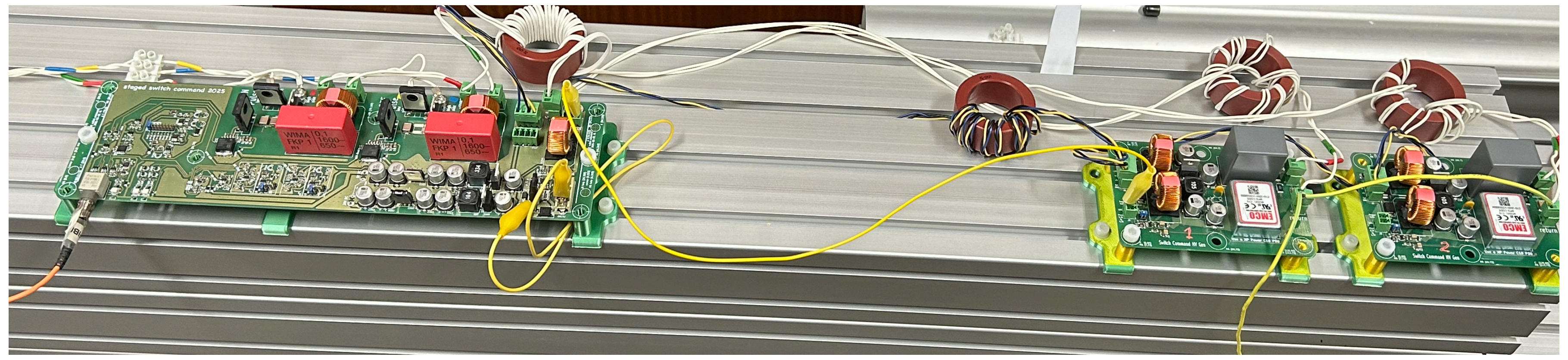
5 High temperature HF - DPS with pulsed solenoid B field, Sodium/Potassium - Sodium plasma demonstration (> 2027)

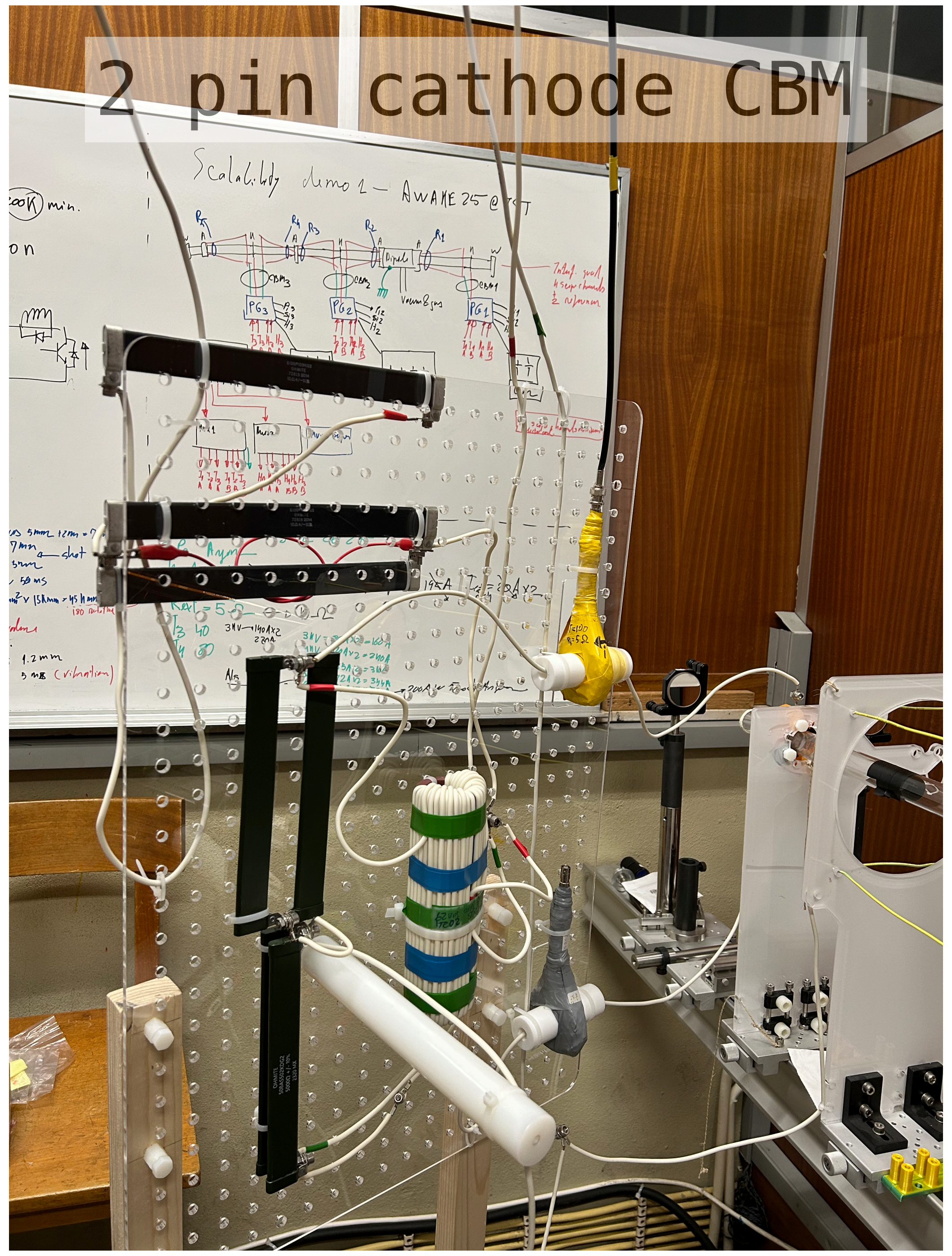
6 High temperature HF - DPS with constant solenoid B field, Sodium/Potassium - continuous operation demonstration (> 2027)

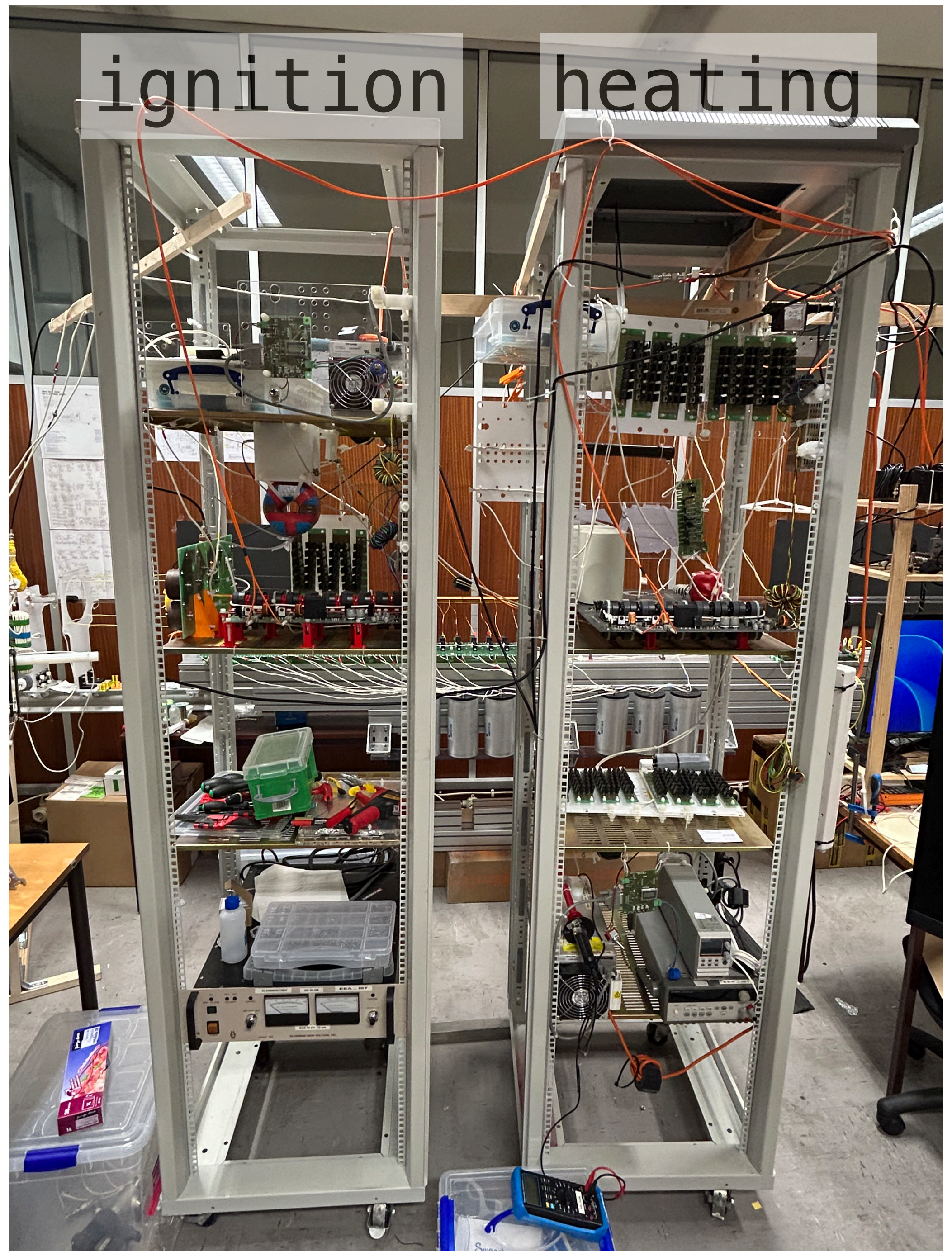
ALiVE DPS with pulsed solenoid field - full first ionisation

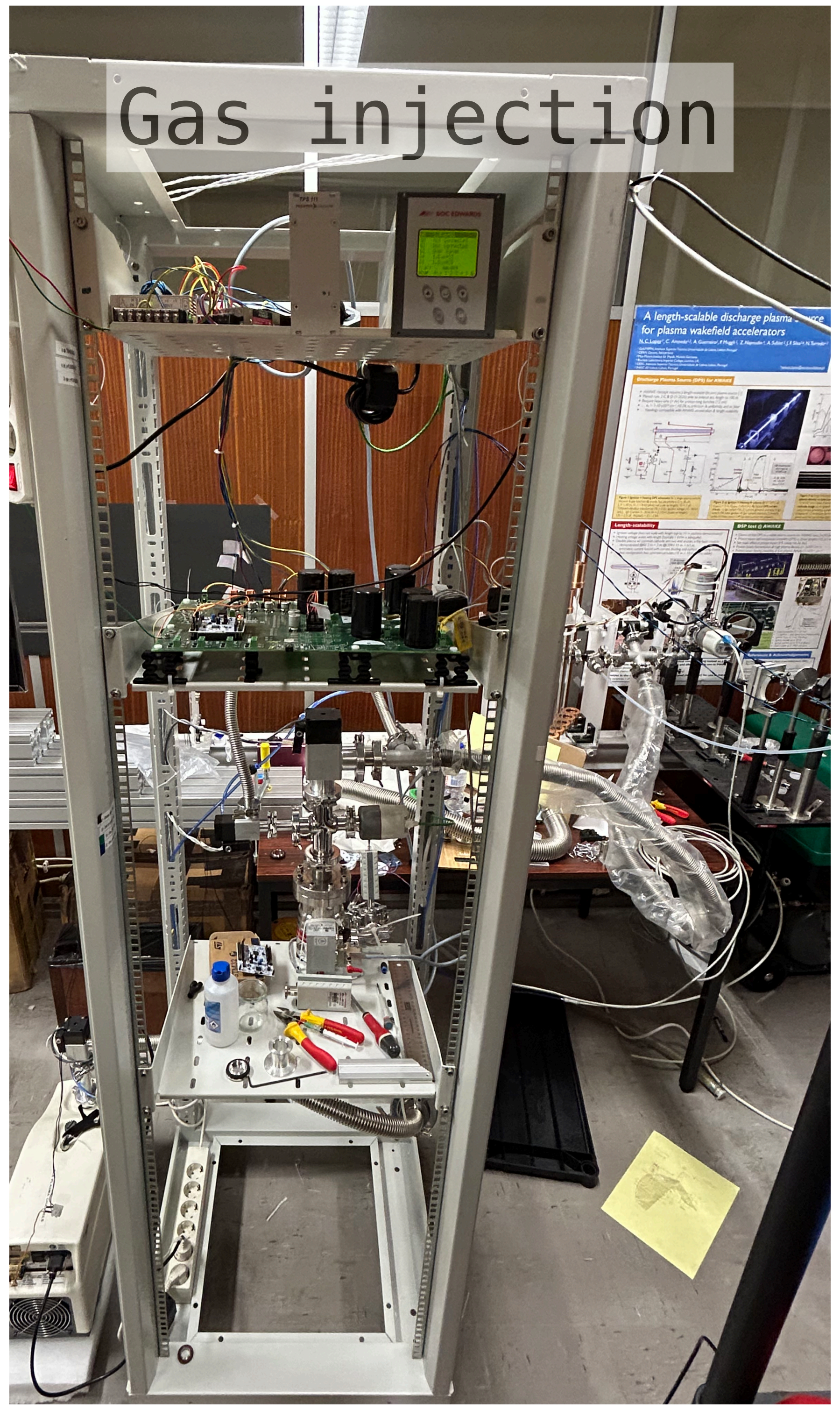


B field switch command









ALiVE DPS with pulsed solenoid field - full first ionisation

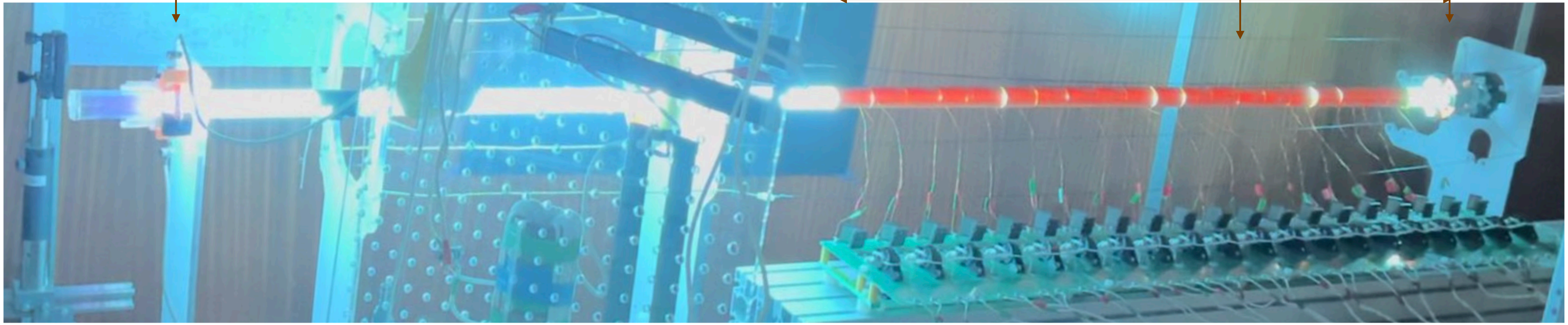
2 pin cathode

Low inductance solenoid
20 x 120 turns

Ring anode

L_d = 1.99 m

L_B = 1.11 m



80 V -> 36 A -> 0.1 T
…
560 V -> 252 A -> 0.7 T
800 V -> 360 A -> 1.0 T

20 x synchronous switches 1.2 kV 400 A
Cap bank w/ 7.2 mF

ALiVE DPS with pulsed solenoid field - full first ionisation

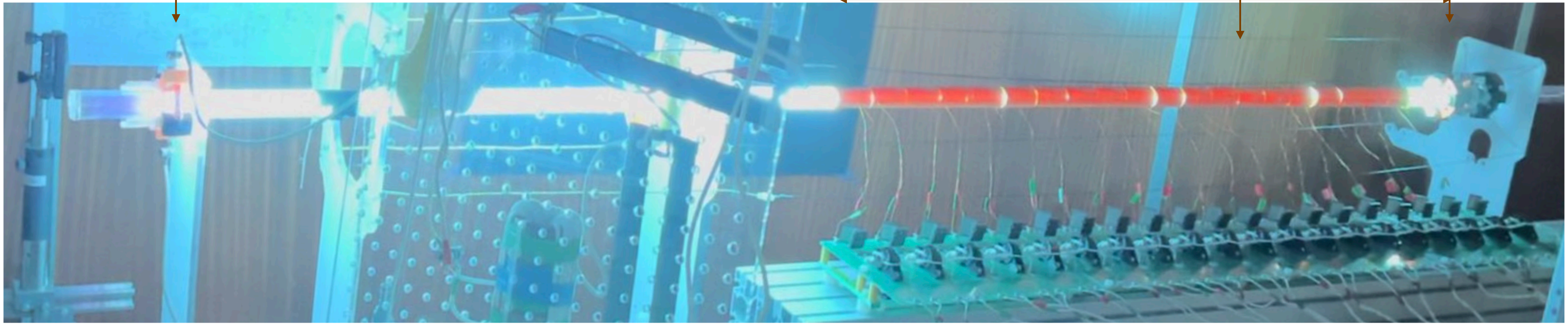
2 pin cathode

L_d = 1.99 m

Low inductance solenoid
20 x 120 turns

Ring anode

L_B = 1.11 m



80 V -> 36 A -> 0.1 T
…
560 V -> 252 A -> 0.7 T
800 V -> 360 A -> 1.0 T

$$B = \mu_0 \frac{NI}{l} = 1.257 \times 10^{-6} [Hm^{-1}] \frac{N[turns]\ I[A]}{l[m]}$$

$$L = \mu_0 \frac{N^2 A}{l} = 1.257 \times 10^{-6} [Hm^{-1}] \frac{(N[turns])^2\ A[m^2]}{l[m]}$$

$$v_i = \sqrt{\frac{2 \frac{3}{2} kT}{m_i}} = \sqrt{\frac{2 \frac{3}{2} 1.3807 \times 10^{-23} [JK^{-1}] T[K]}{6.63e{-}26[kg](Argon)}} = 2692 - 3807\ [ms^{-1}]$$

$$L_{ri} = \frac{m_i v_i}{eB} = \frac{6.63 \times 10^{-26} [kg] v_i [ms^{-1}]}{1.6022e{-}19[C] B[T]} = \frac{1.11[mm]}{B[T]} - \frac{1.58[mm]}{B[T]}$$

Argon example…

… goal L_{ri} << R_{tube} = 13 mm

… ≤ 1 T solenoid B required

ALiVE DPS with pulsed solenoid field - full first ionisation

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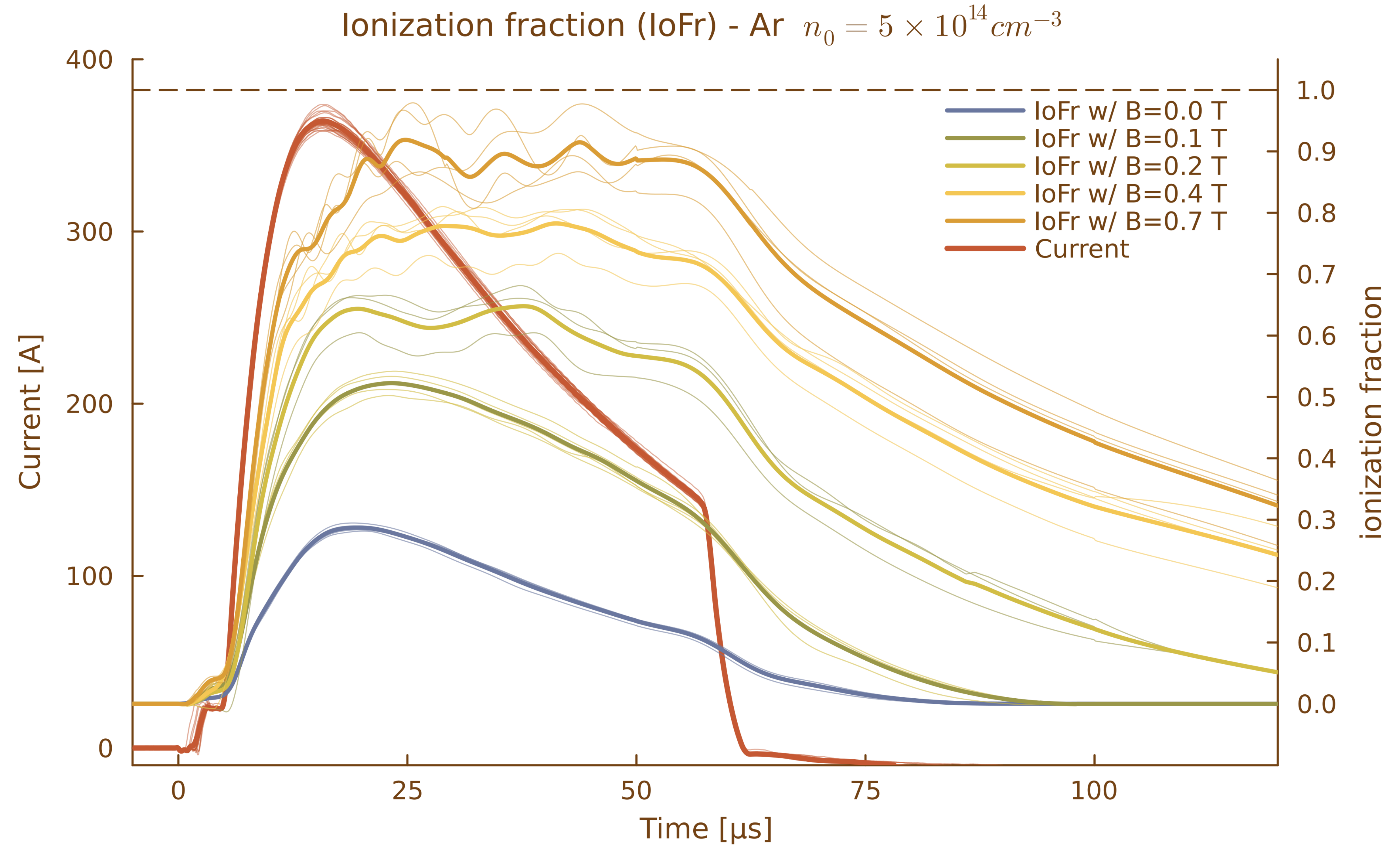
Preliminary results…

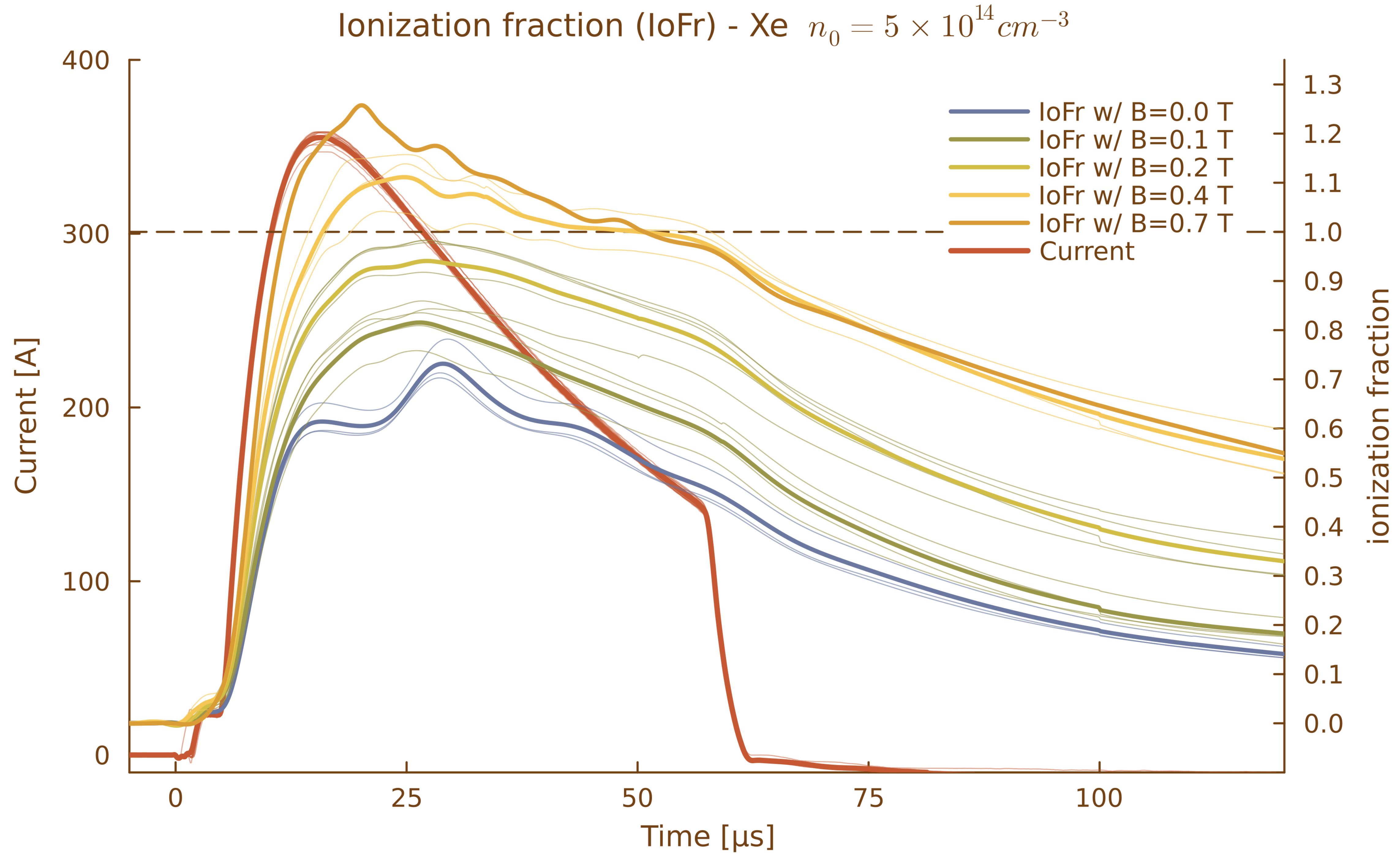
Argon



Ionisation fraction monotonically increases w/ B

Close to 90 % w/ 360 A / 0.7 T

Xenon



Second ionisation reached in Xenon

Close to 110% w/ 360 A / 0.4 T

Close to 125 % w/ 360 A / 0.7 T

Conclusion: Modest solenoid B field (∼0.4T) significantly reduces plasma cooling at tube walls and will allow ∼ full first ionisation

Future work: Reduce solenoid vibrations, full length solenoid, shorter current pulses, 600 A pulses, achieve 100% first ionisation in Ar/Xe