Prospects and challenges for high-repetition-rate plasma sources for future colliders

Simon Hooker & Richard D'Arcy

Department of Physics & John Adams Institute
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Challenges

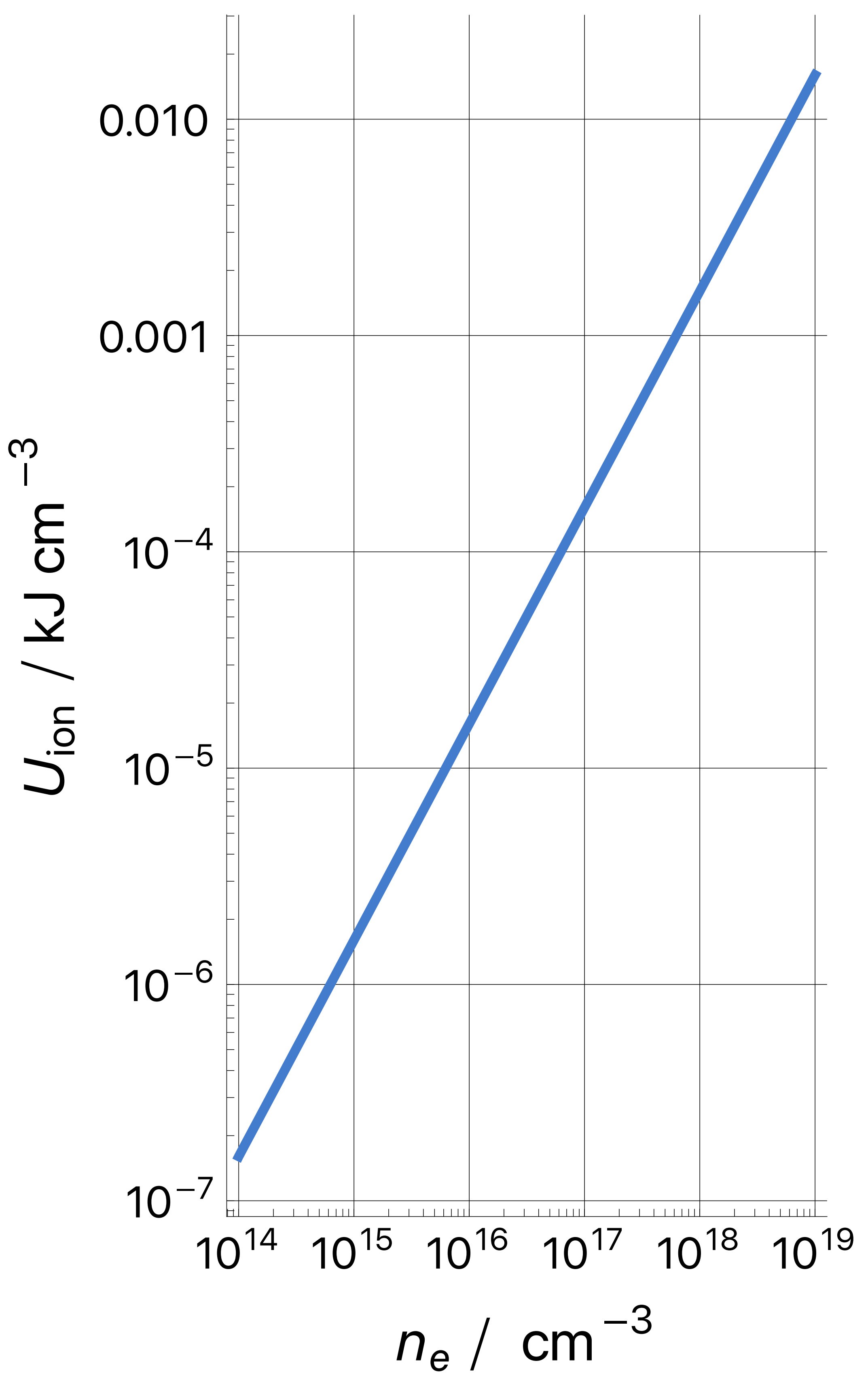
Orders of magnitude I: Estimate of stored energy

$$U_{\rm ion} = n_e E_{\rm ion}$$

$$U_{\rm wake} = \frac{1}{2}\epsilon_0 E_0^2$$

- The energy density of the wakefield is ~ 3 orders of magnitude than that required to generate the plasma
- Note: 1 kJ cm-3 gives ~ 10 J total energy for a 100 μm × 100 μm × 1 m plasma
- Removing this residual energy after acceleration is the challenge

Energy density to ionize plasma ($E_{\rm ion}$ = 10 eV)



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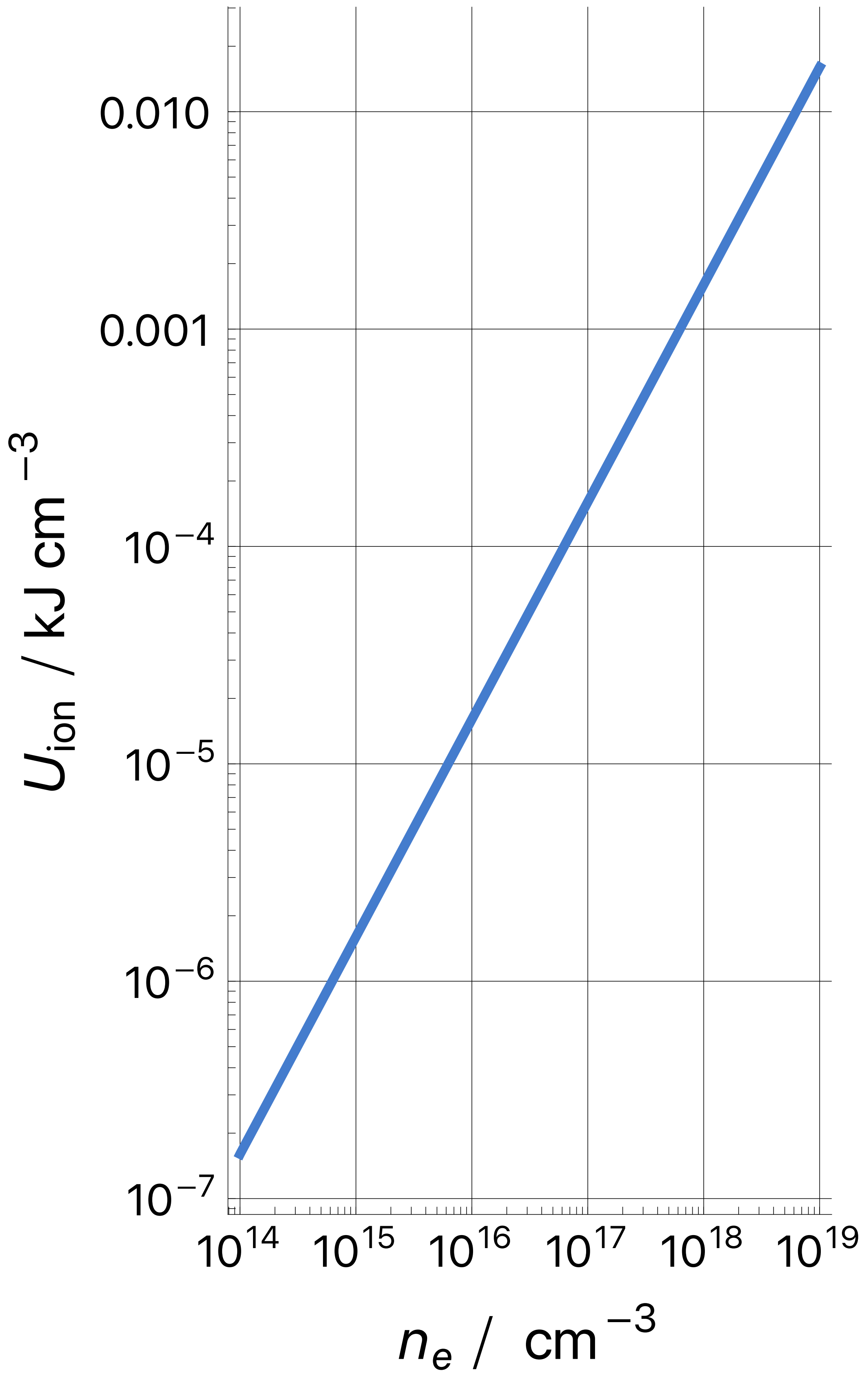
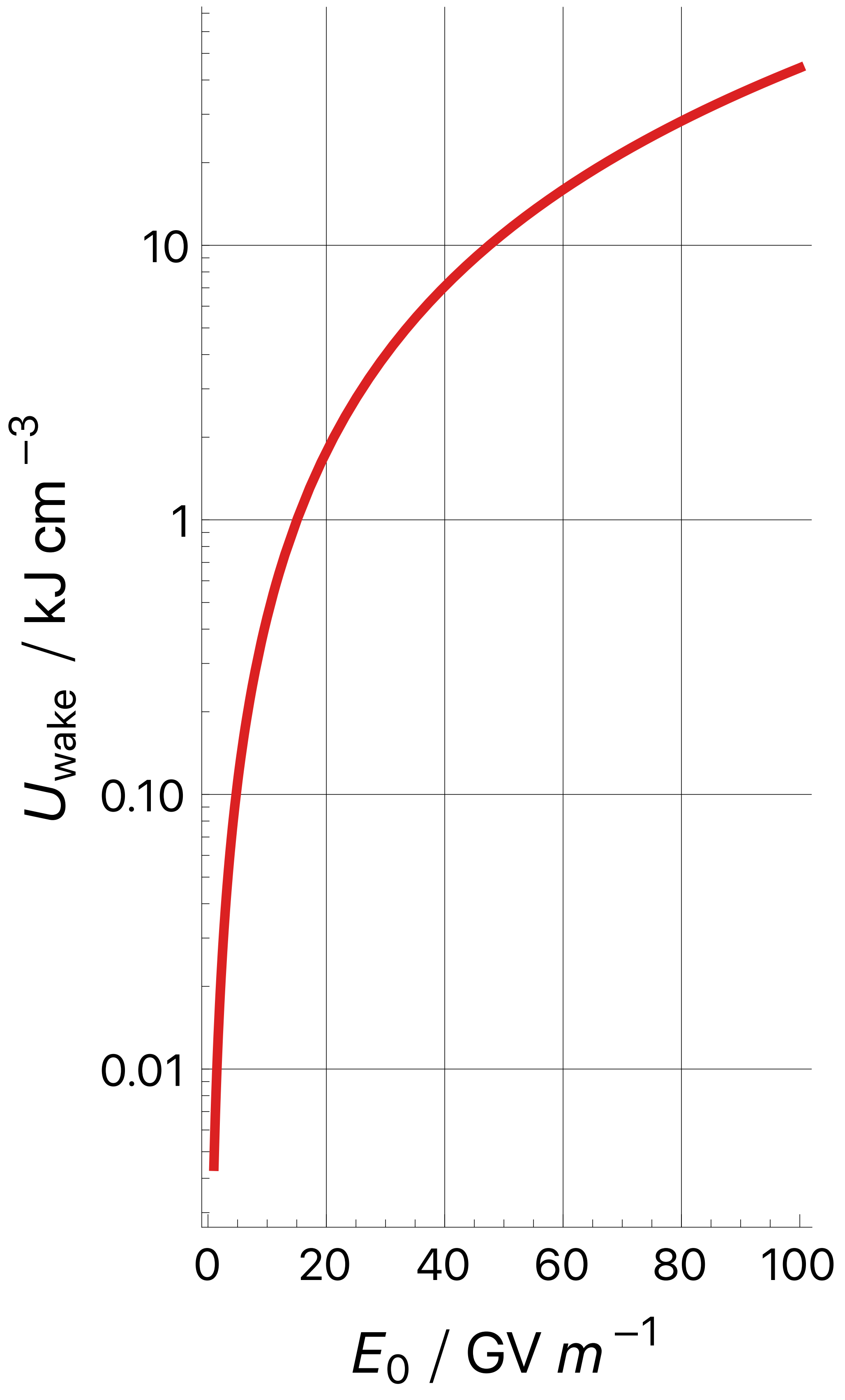


Energy density in wakefield



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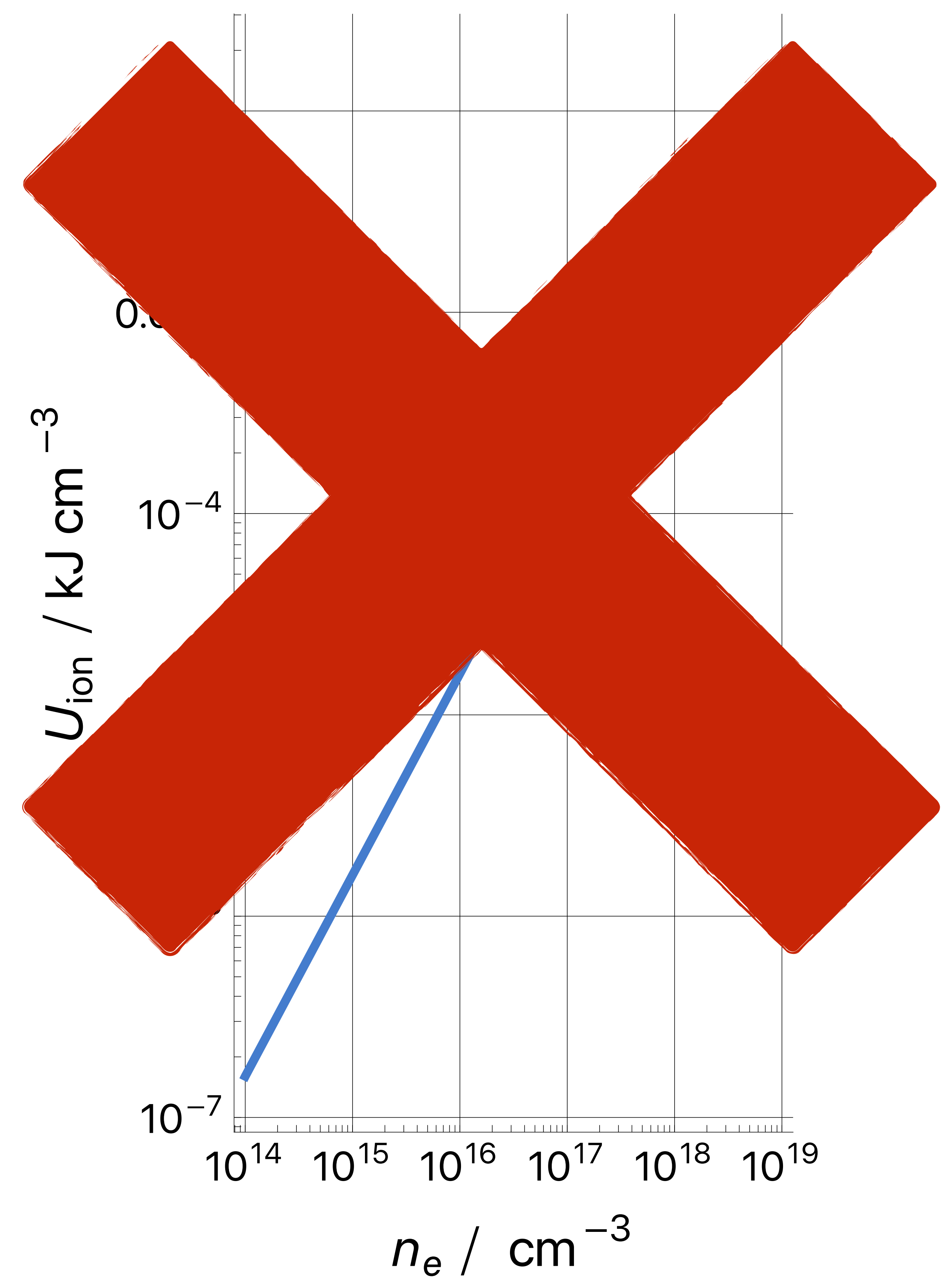

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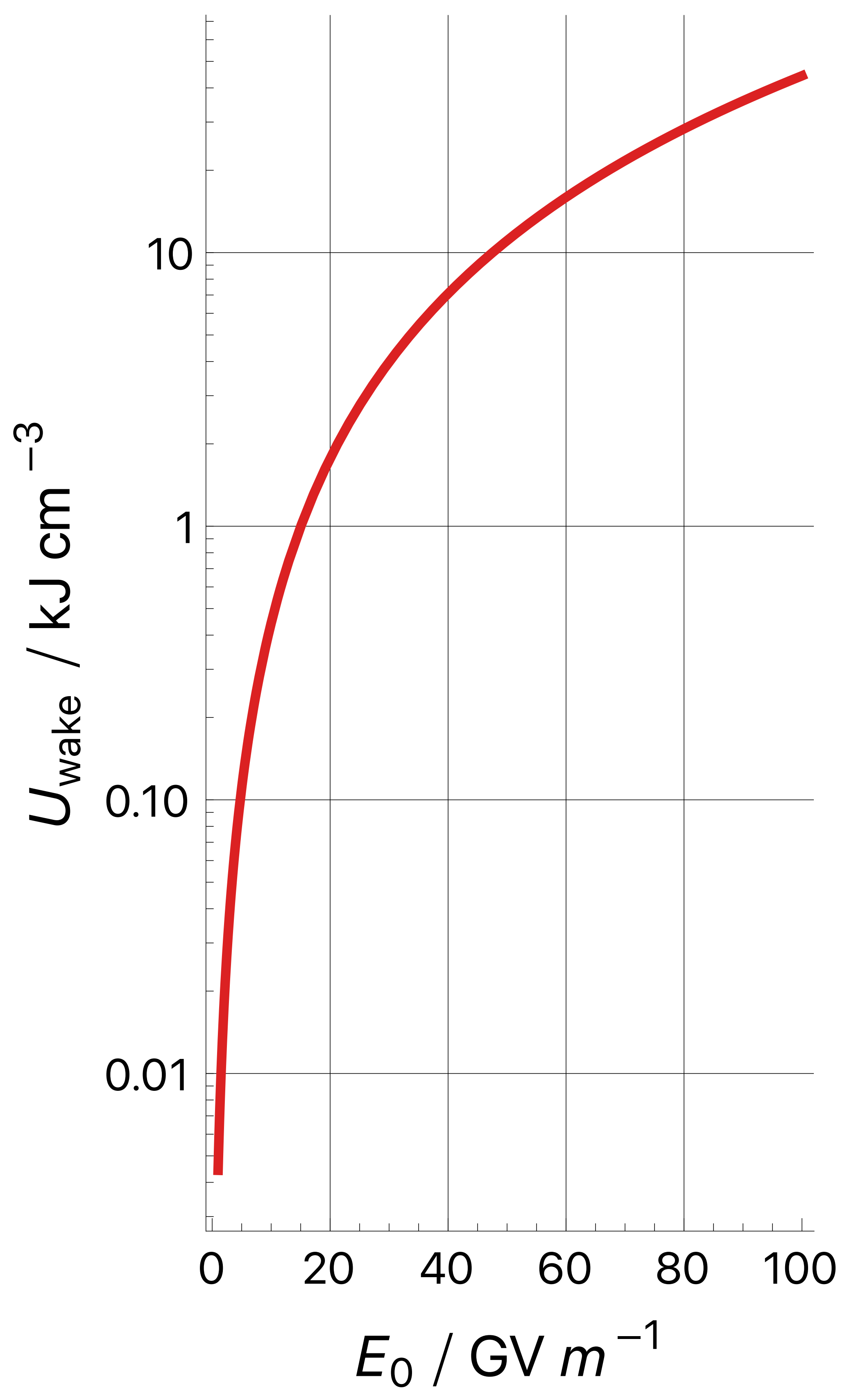

Orders of magnitude II: Required power extraction

"Physics efficiency"

$$\frac{dP_{\rm cool}}{ds} = E_z \quad Q_b f_{\rm rep} \quad \left(\frac{1}{\eta} - 1\right)$$

"Space efficiency"

"Energy efficiency"

Parameter	Energy gain per stage (GeV)	Cell length (m)	Gradient (GV/m)	Charge (nC)	f_{rep} (kHz)	Wake-to-beam efficiency	**Avg. cooling gradient (kW/m)**
LWFA collider (1, 3, 15 TeV)	5	1.7	3.3	0.2	50	0.75	**11**
HALHF	32	5	6.4	1.6	10	0.53	**91**
XFEL Booster	10	2	5	0.3	10	0.42	**21**

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"Energy efficiency"

CLIC cooling is O(10 kW / m)

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The challenge

- After acceleration plasma will:
  - Contain wakefield energy
  - Have non-uniform densities of various species
  - Have gradients of temperature & other properties
  - Be at least partially ionized
  - …

- Before the next drive pulse the plasma needs either to:
  - Recover
    - Redistribute to uniform density
    - Recombine
    - Cool
    - …
  - Be replaced / refreshed

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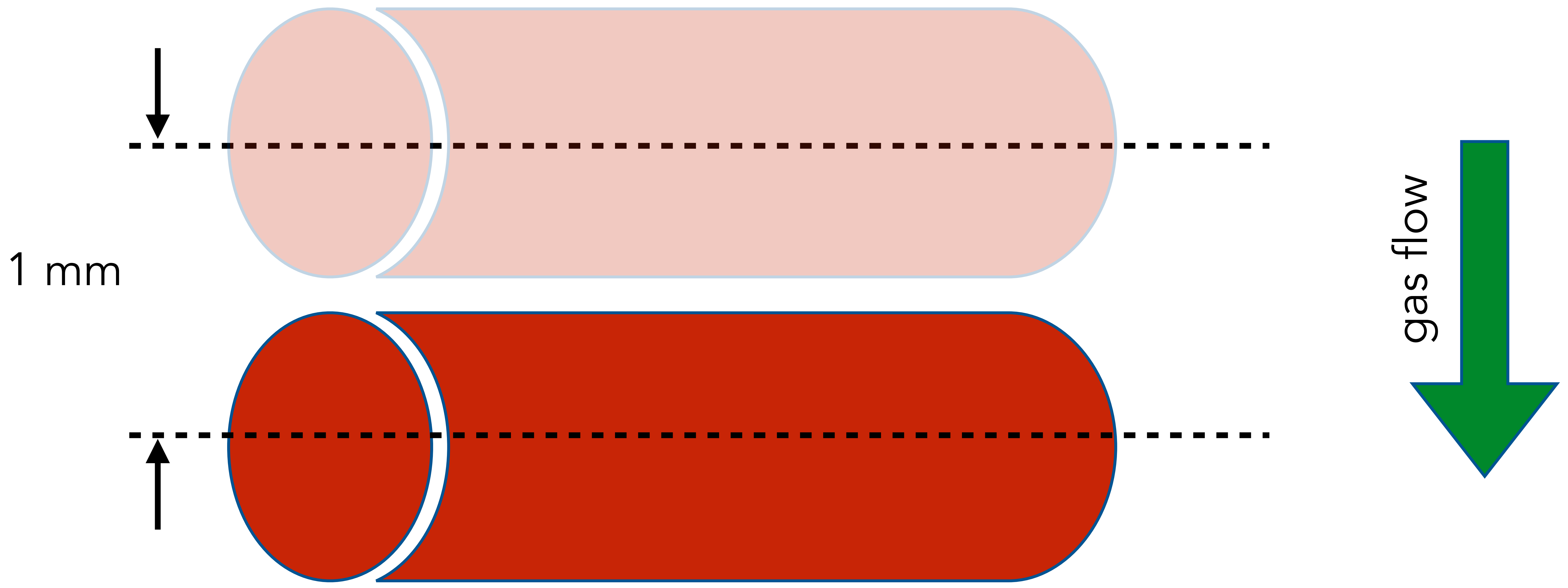
There are (at least) four possible strategies:

1. Move the plasma of the way
2. Do nothing (wait)
3. Manipulate existing re-combining plasma
4. Energy recovery

Strategy 1: Move the plasma

$$c_s = \sqrt{\frac{\gamma k_B T}{M}} \approx 1.3\,\mathrm{km\,s^{-1}}$$



- Assume can move gas at speed ~ c_s
- Time to move by 1 mm ~ 1 μs
- Max repetition rate ~ 1 MHz

Strategy 2: Wait

- Before the next drive pulse the plasma needs either to:
  - Recover
    - Redistribute to uniform density
    - Recombine
    - Cool
    - …

- How long does this take?

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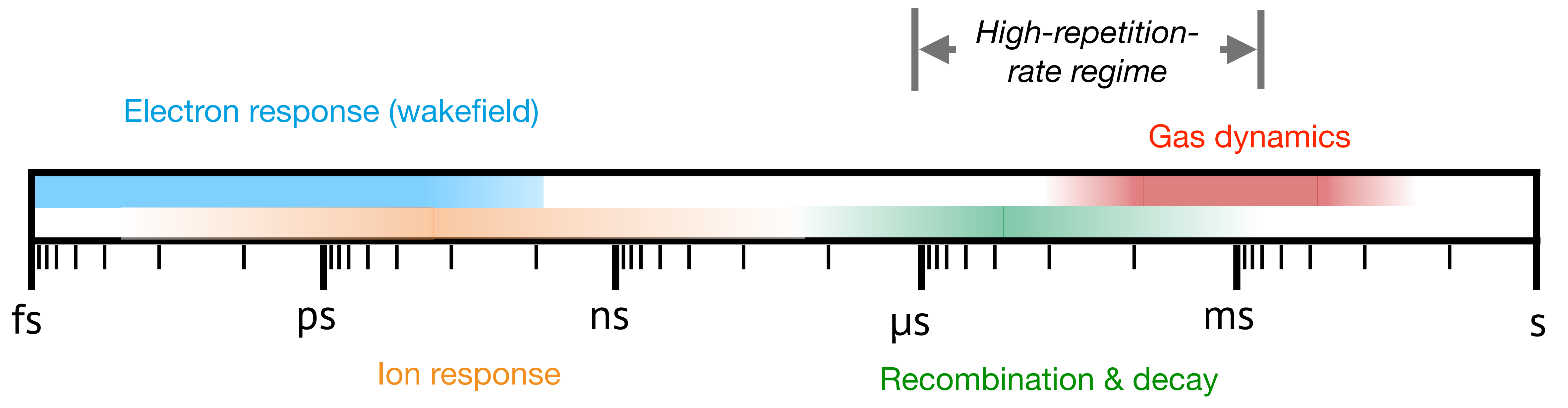
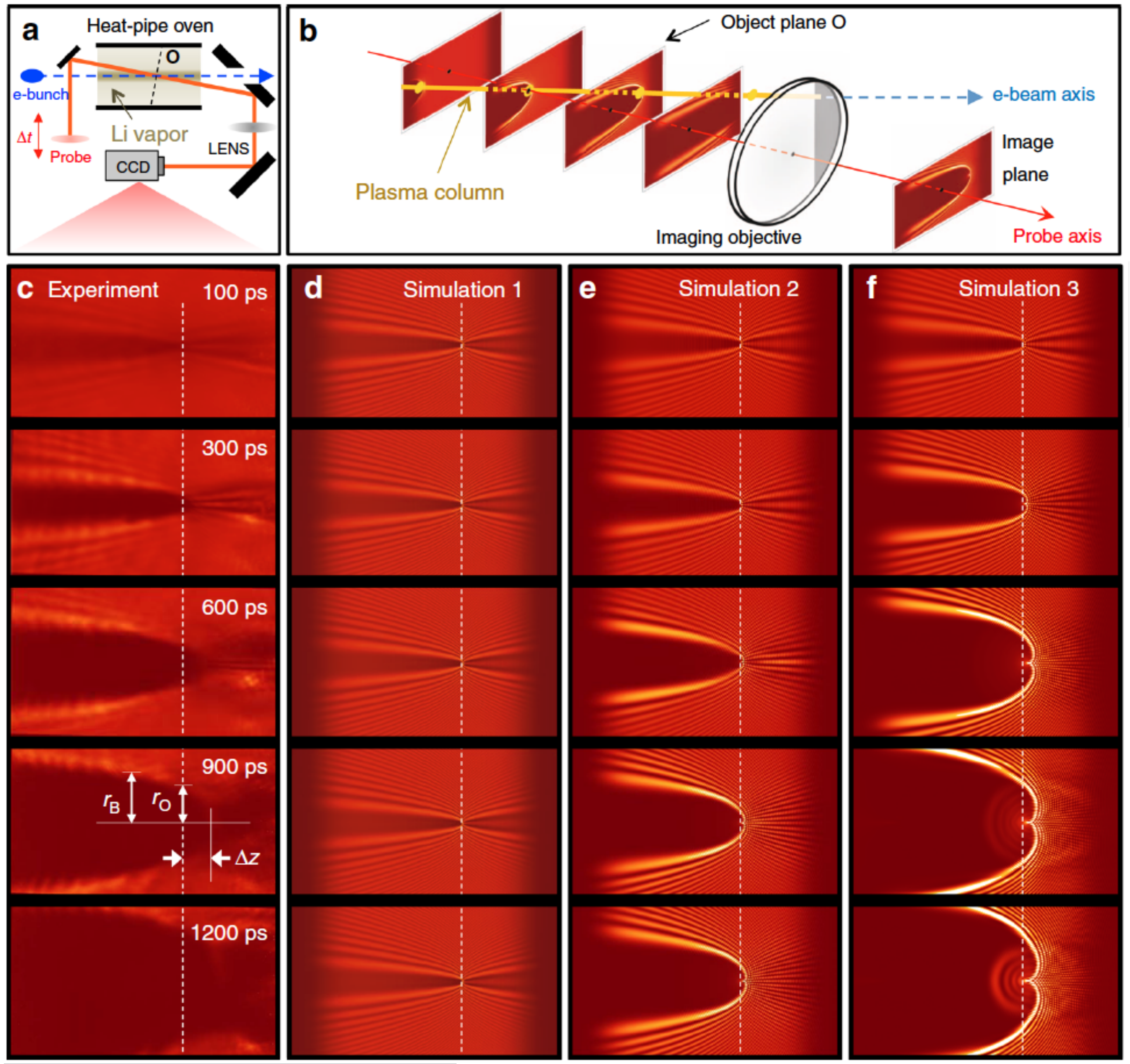


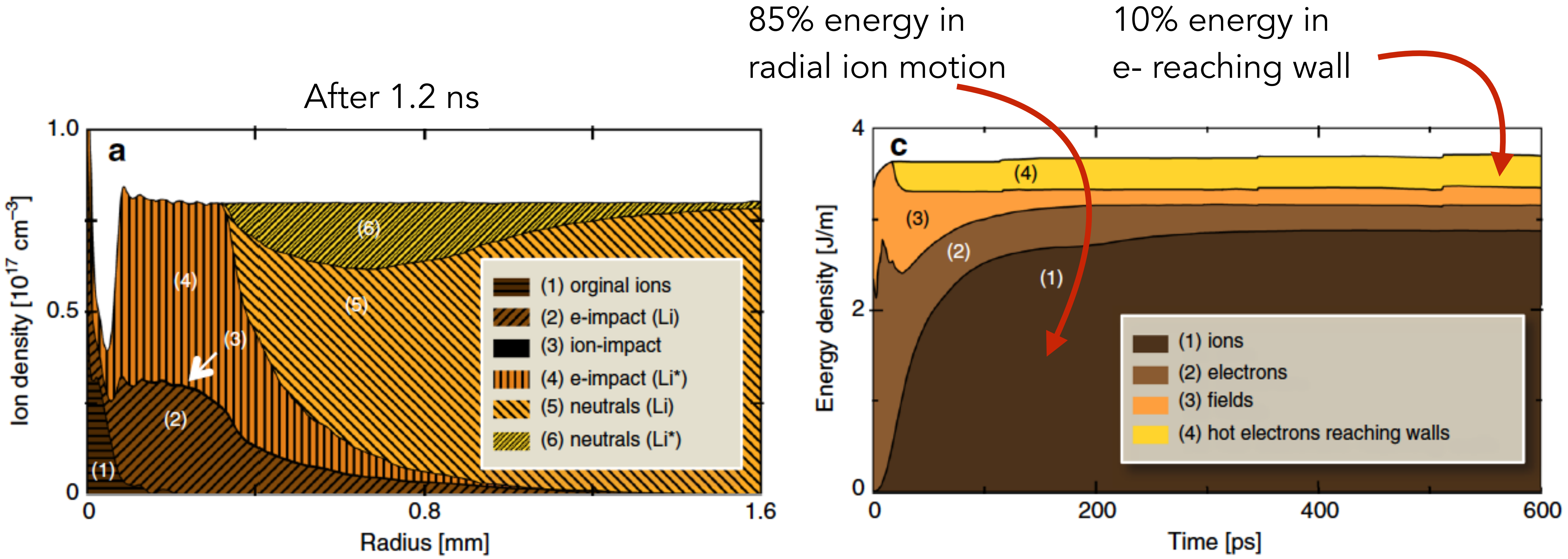
Some processes to consider:

- Wakefield decay
- Free-streaming ions
- Additional ionization
- Heat conduction in plasma & gas
- Density redistribution
- Plasma expulsion
- Electron-ion recombination
- Radiation
- …

Timescales: Initial ion dynamics

R. Zgadzaj *et al.*, Nat. Commun **11**, 4753 (2020)





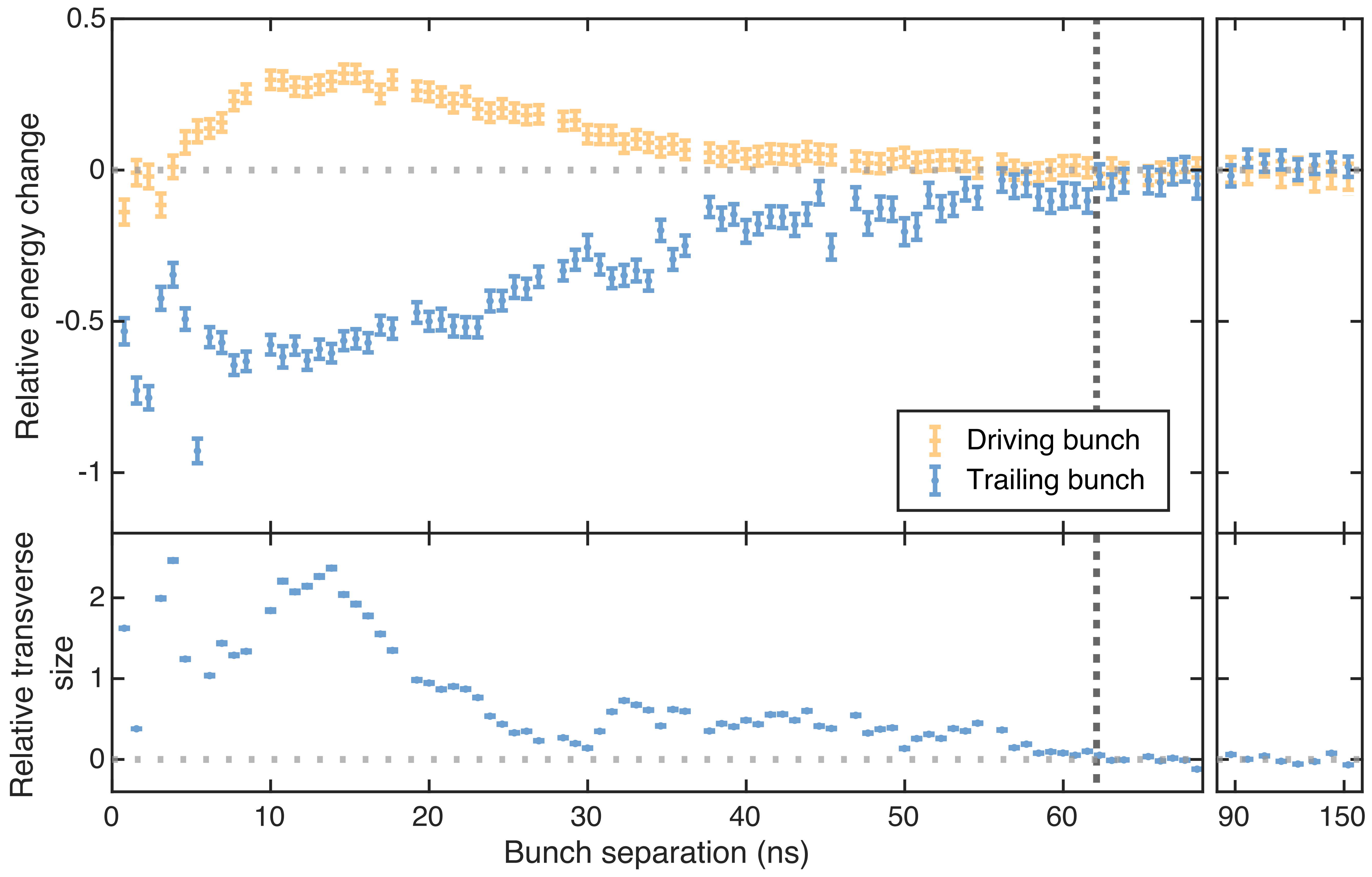
<u>Experiment parameters</u>

E_{drive}: 20 GeV
Q_{drive}: 2 nC
σ_r: 30 μm
σ_z: 55 μm
n_{Li}: 8×10^{16} cm^{-3}

- Initial wake breaks, expelling fast electrons from the plasma
- Radial electric fields propel ions outward at tens of keV while escorting electrons
- Outwardly streaming electrons and ions ionize and excite surrounding neutral lithium, expanding plasma volume several hundred-fold.

Timescales: Total plasma recovery time

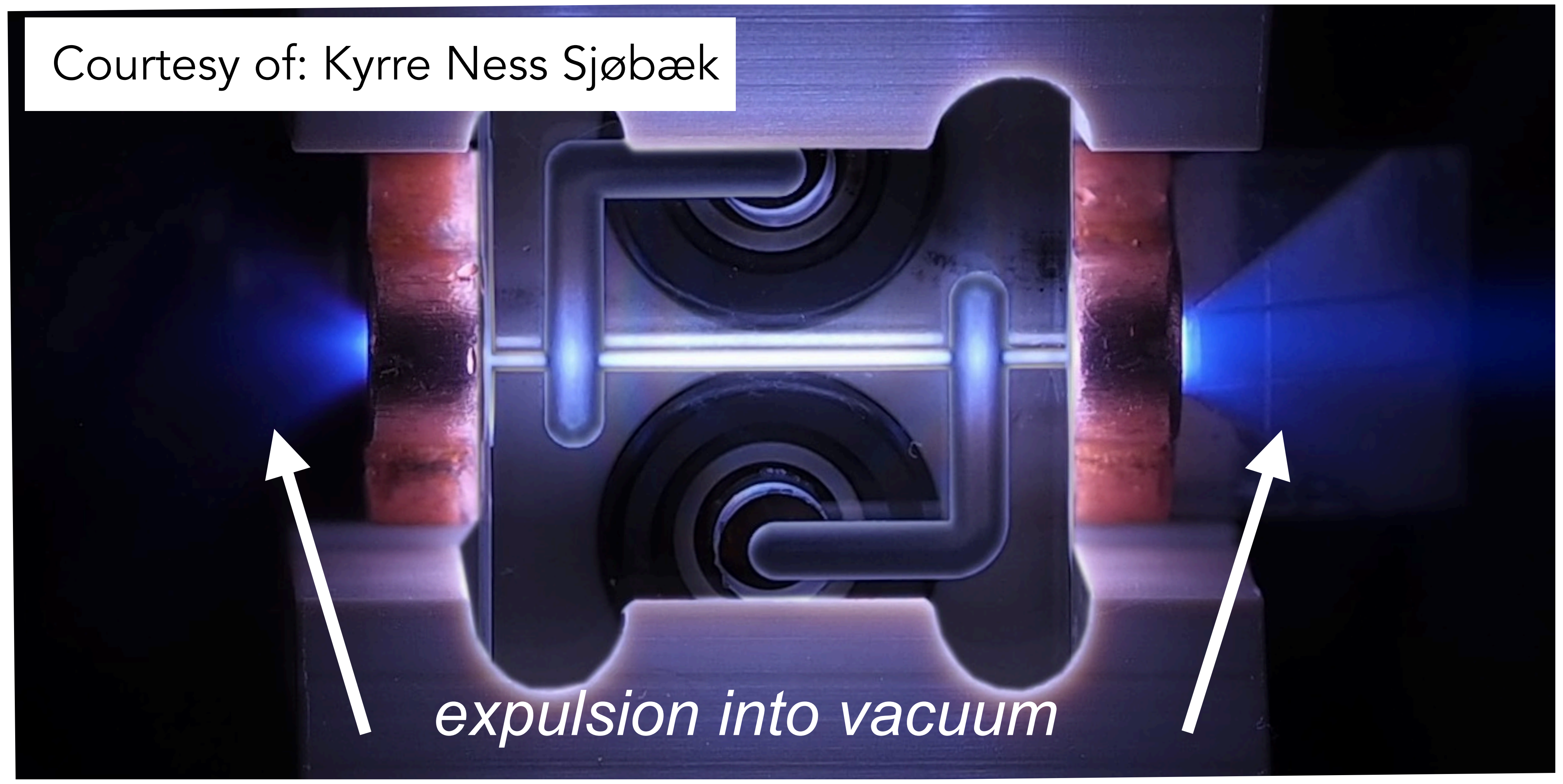
R. D’Arcy *et al.*, *Nature* **603**, 58-62 (2022)

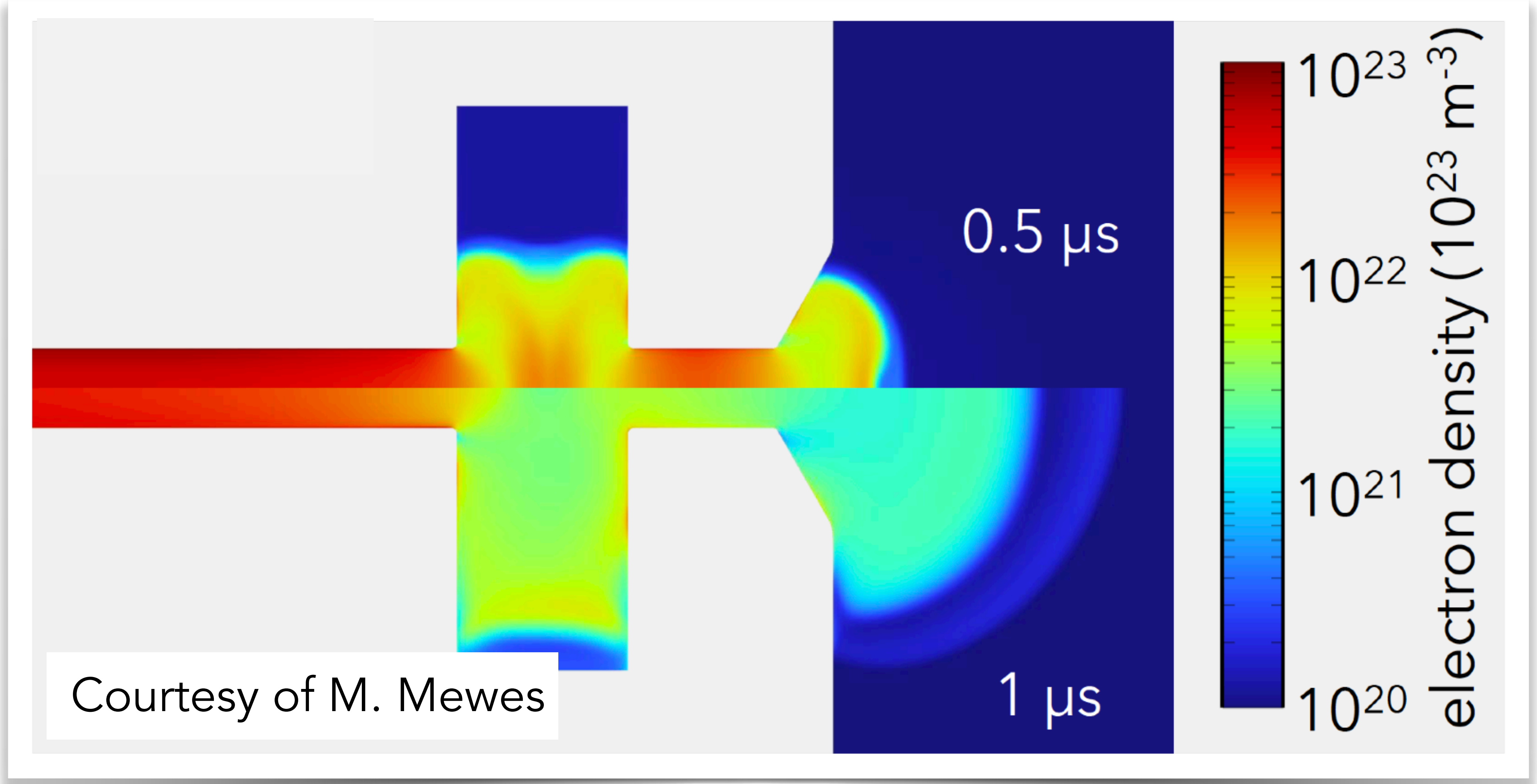


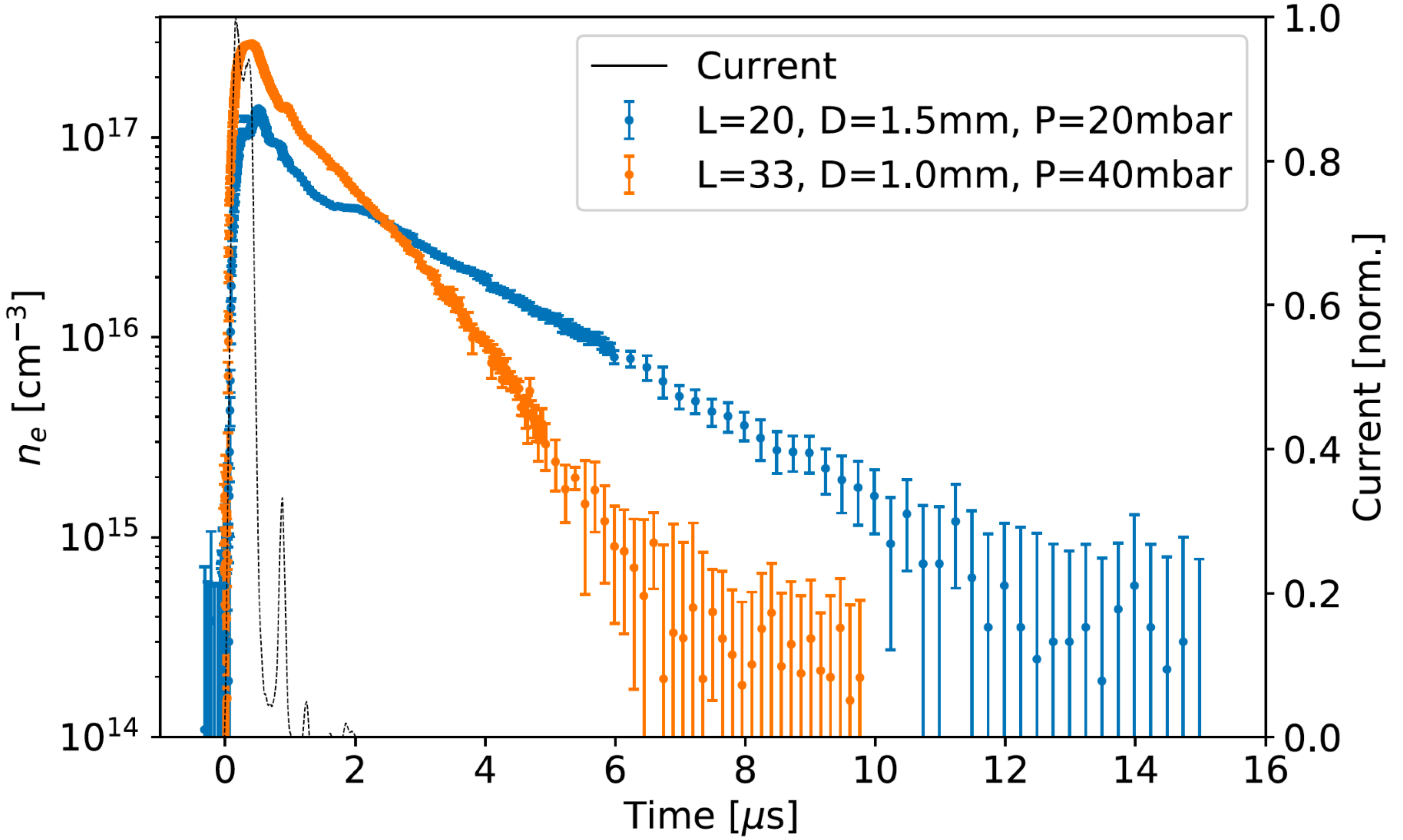
- Plasma recovers in < 100 ns ⇒10 MHz rep-rate in principle …
- Includes effects of:
  - Ion motion
  - Plasma & gas re-distribution
- But does not include mean-power effects, e.g.:
  - Increase in mean plasma temperature

Strategy 3: Manipulate whatever plasma still exists

Garland *et al.*, *Rev. Sci. Instrum.* **92** 013505 (2021)

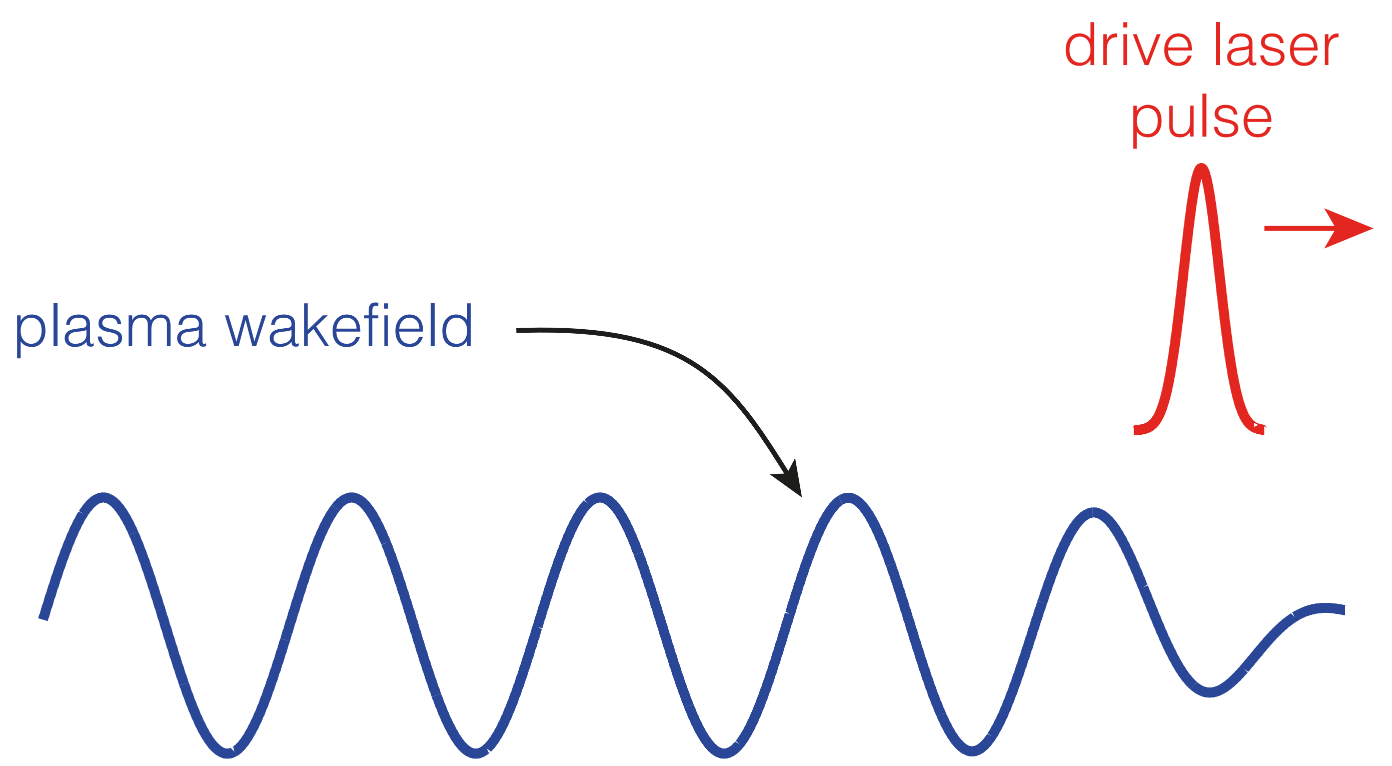






- Timescale for "plasma recovery" ~ 100 ns, but…
- … time to eject / replenish plasma much longer for some geometries
- Will need to manipulate the remaining plasma for a MHz collider i.e. μs timescale ➞ e.g. limit expulsion, counteract recombination

Strategy 4: Energy removal & recovery



- Energy removal
  - Remove unused wake energy with additional trailing driver(s)
- Energy recovery
  - In addition use / convert extracted energy

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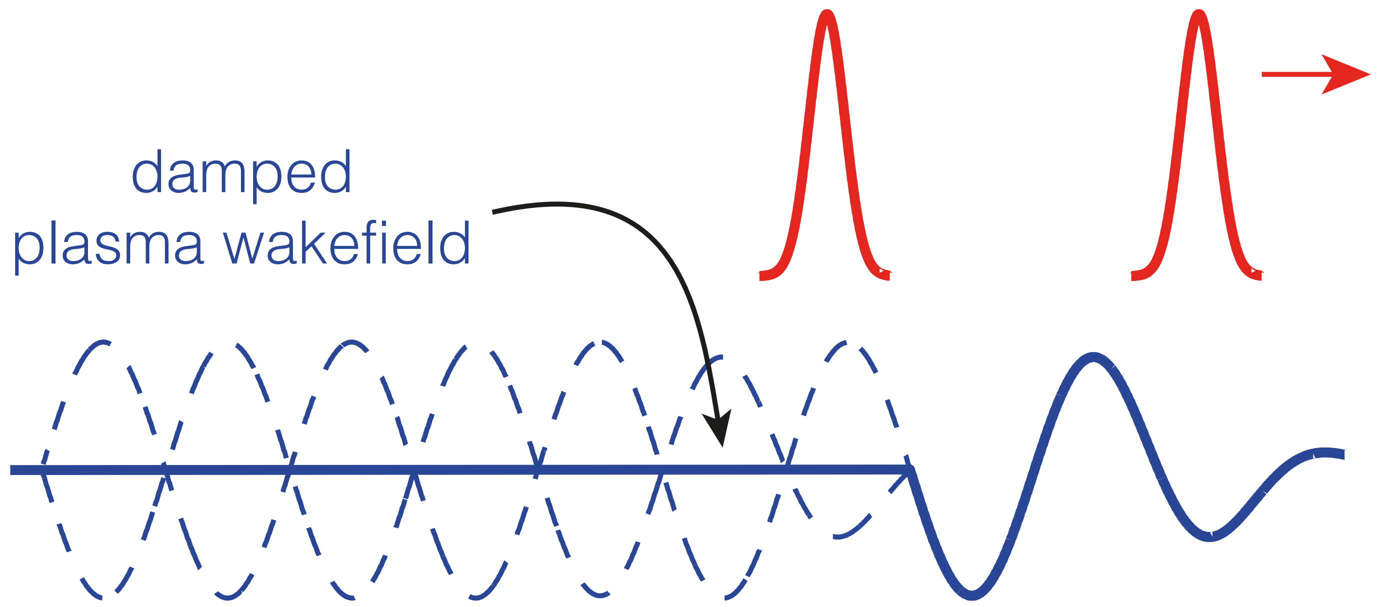

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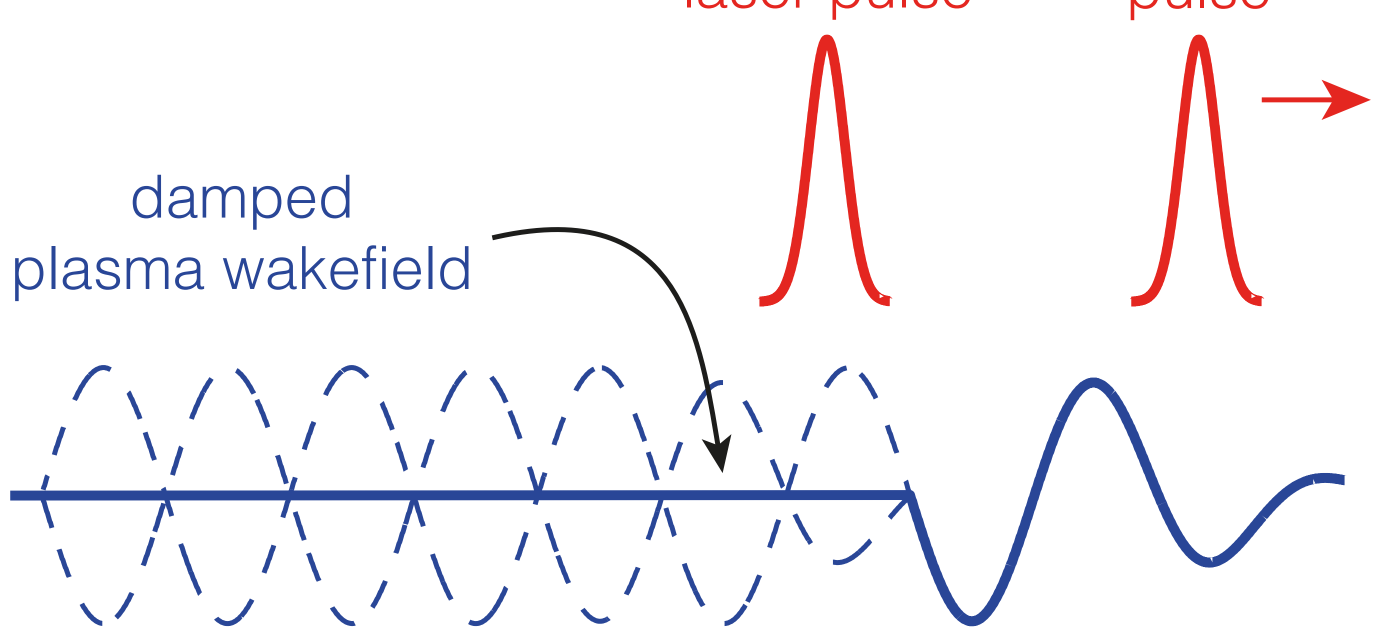

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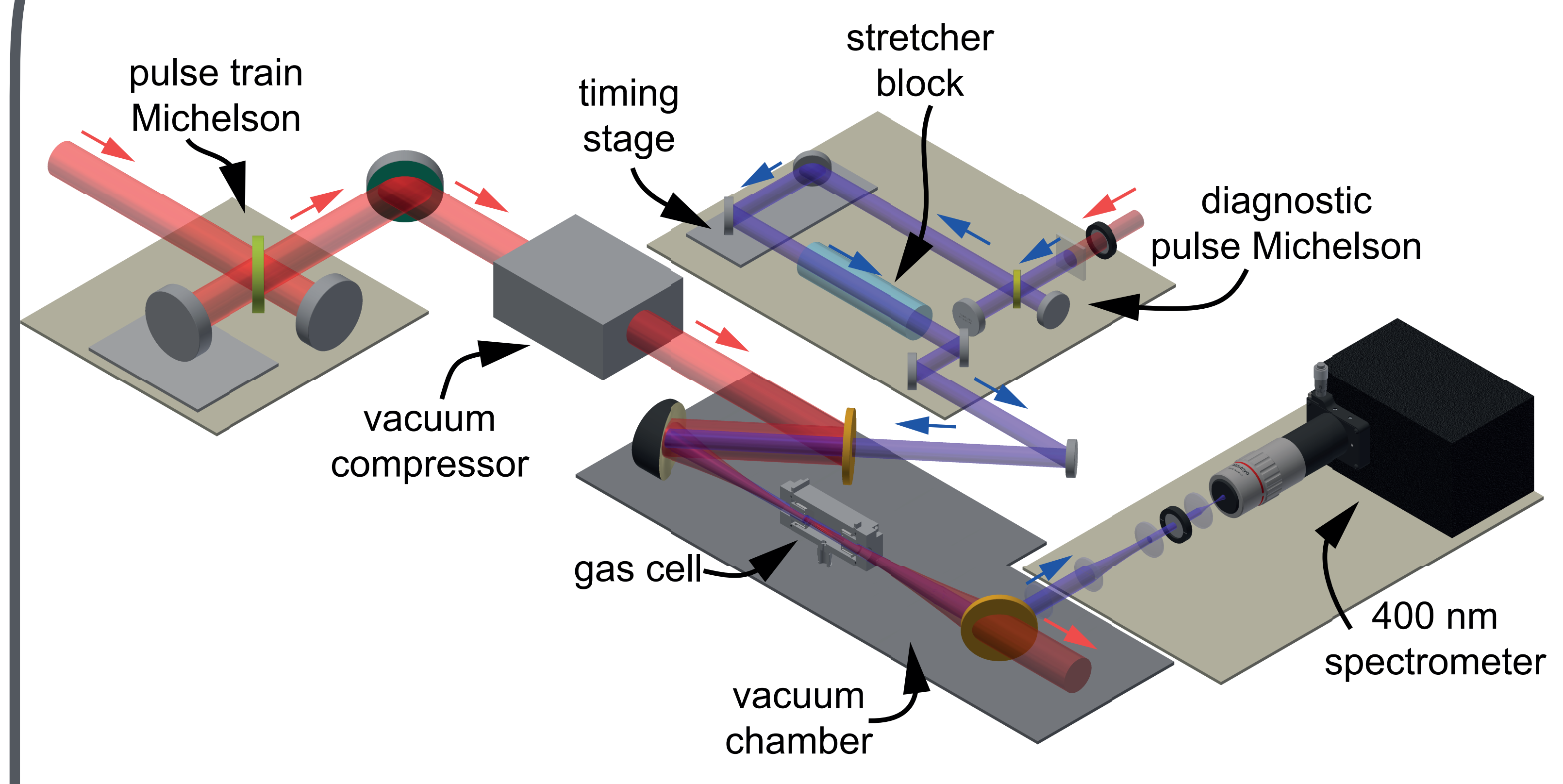
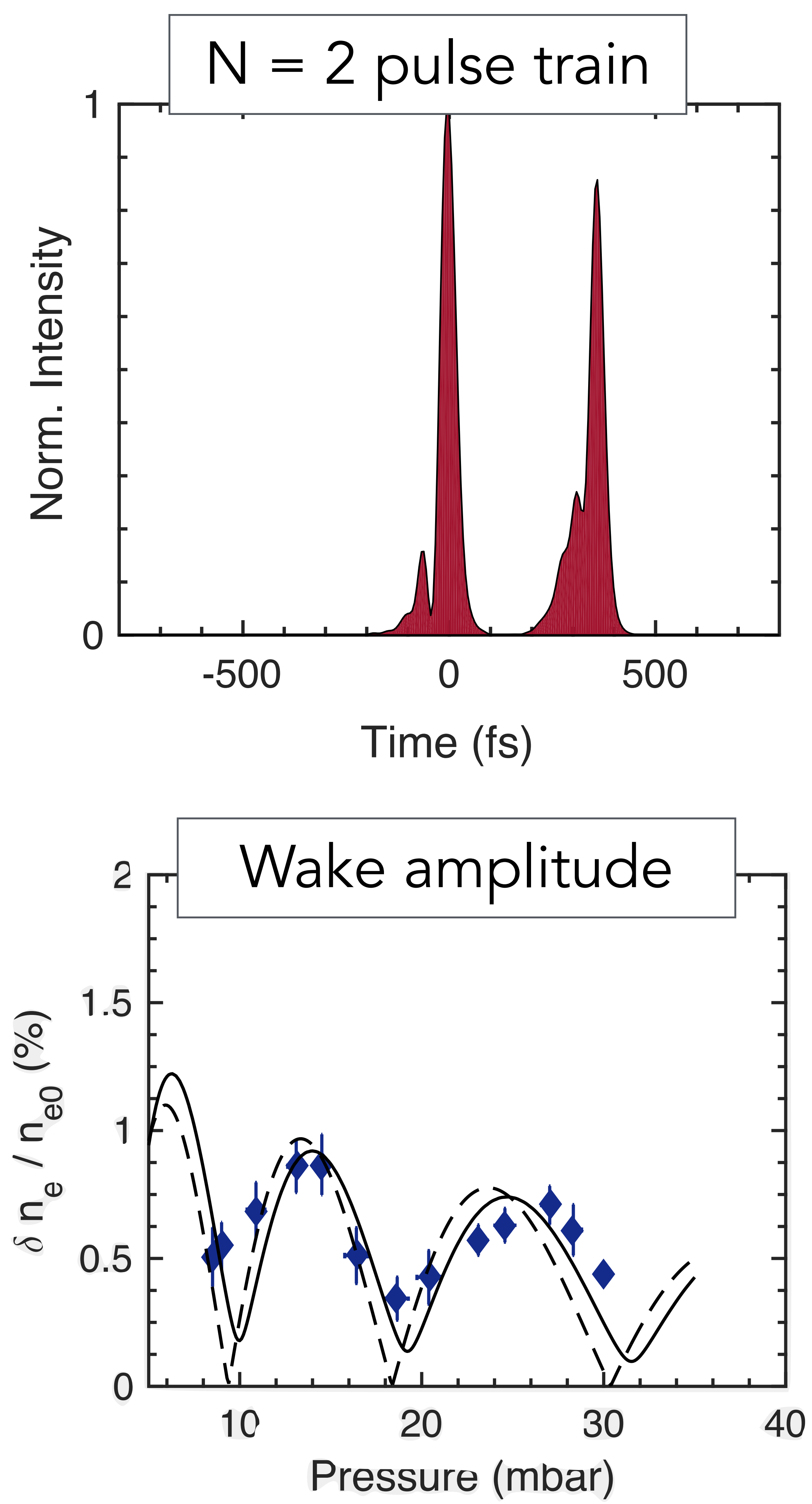
J. Cowley et al. Phys. Rev. Lett. 119 044802 (2017)





Astra TA2 experiments

- 500 mJ, 40 fs Ti:sapphire pulse converted to train of *N* = 1 - 7 pulses
- For *N* = 2 pulses rel. wake amplitude reduced from 0.6% for single pulse to 0.34% by out-of-phase trailing pulse
- ~70 % of wake energy removed!

Progress in developing plasma sources

What do we need from the plasma source?

Common requirements

- Well-defined & controllable density
- Controlled longitudinal density profile at entrance/exit (emittance matching)
- Reproducibility
- Long operating lifetime
- Accessible to diagnostics
- Limited gas load to rest of system
- No windows (to preserve bunch emittance)
- …

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Laser-driven

- Guiding?
- Possibly, control of longitudinal profile (“tapering”)
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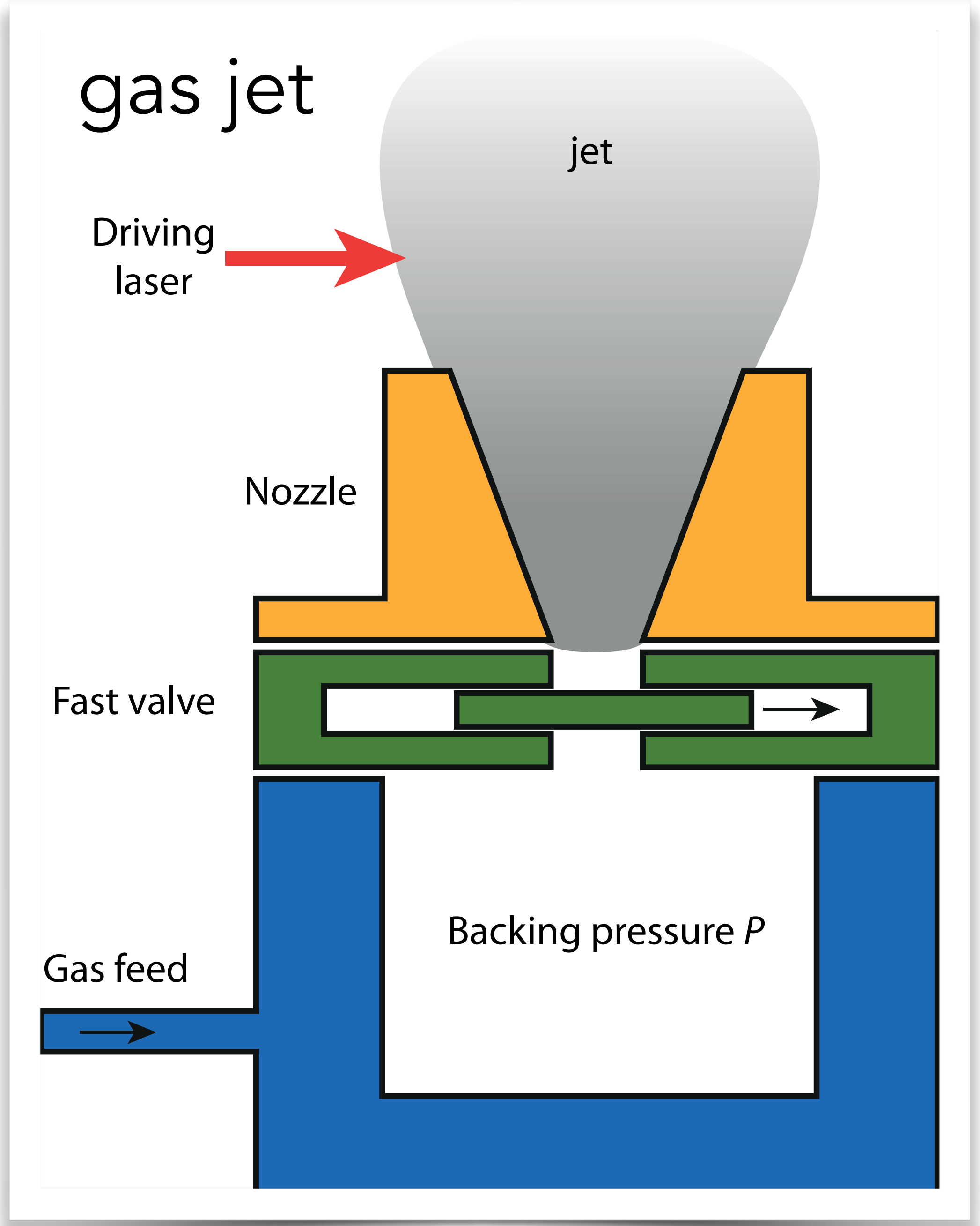
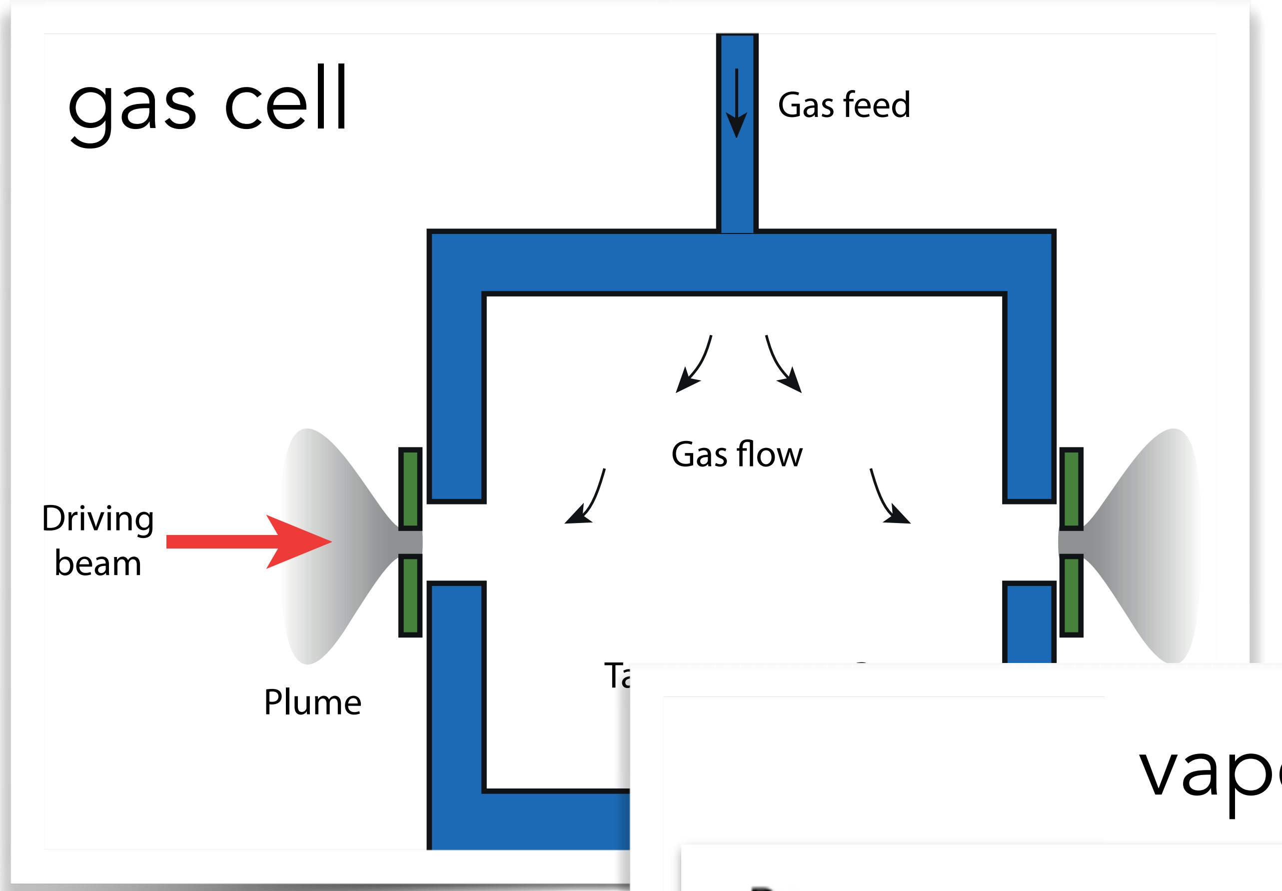
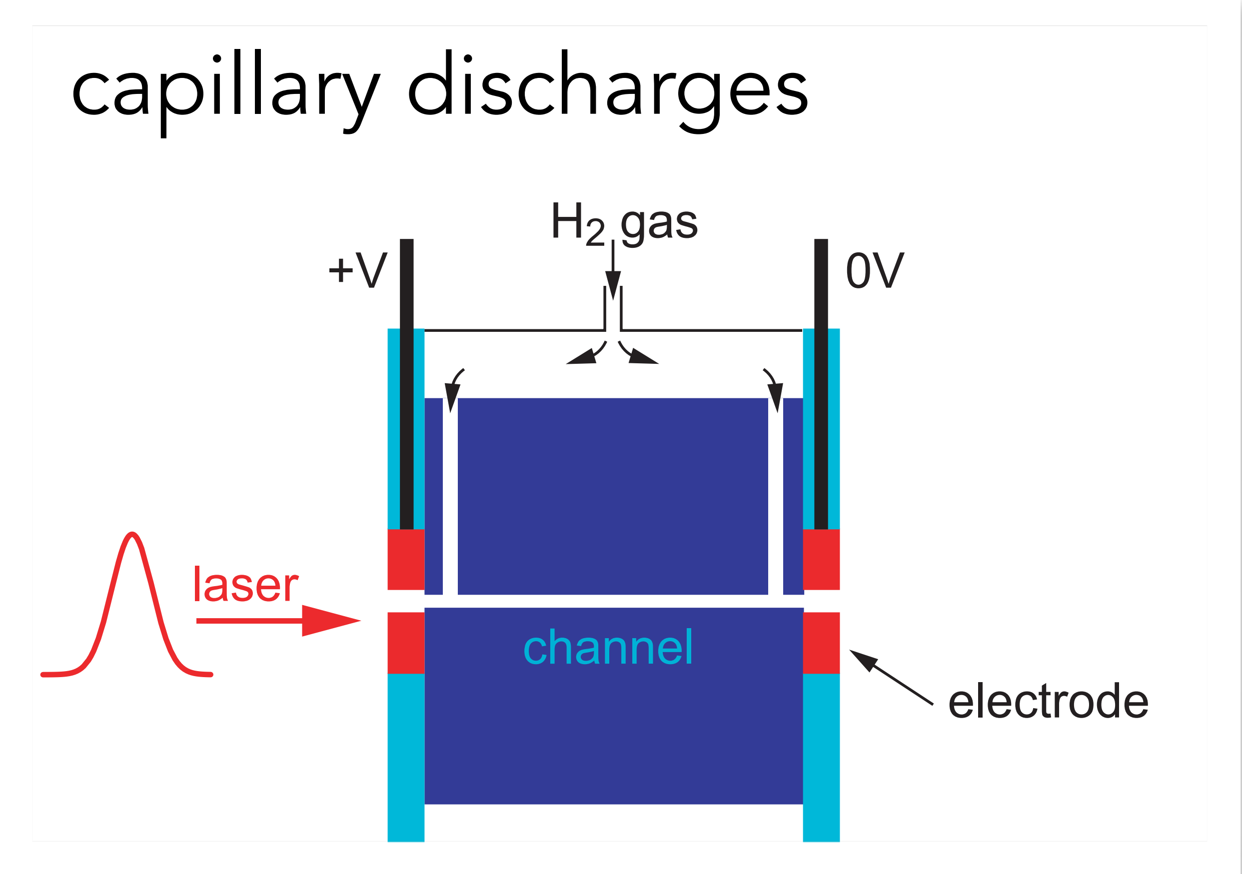
Beam-driven

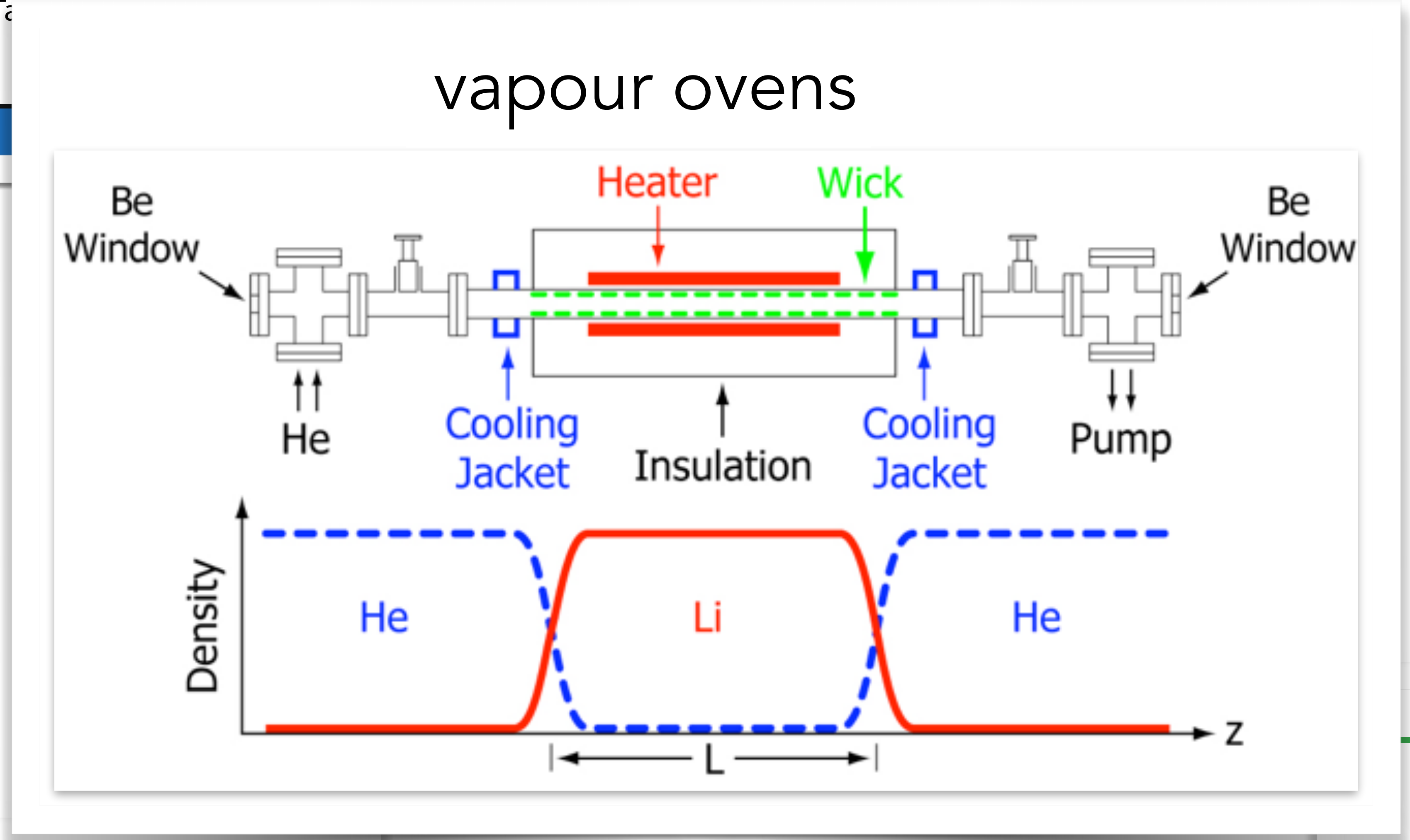
- Provision of laser pulse for ionization?
- …

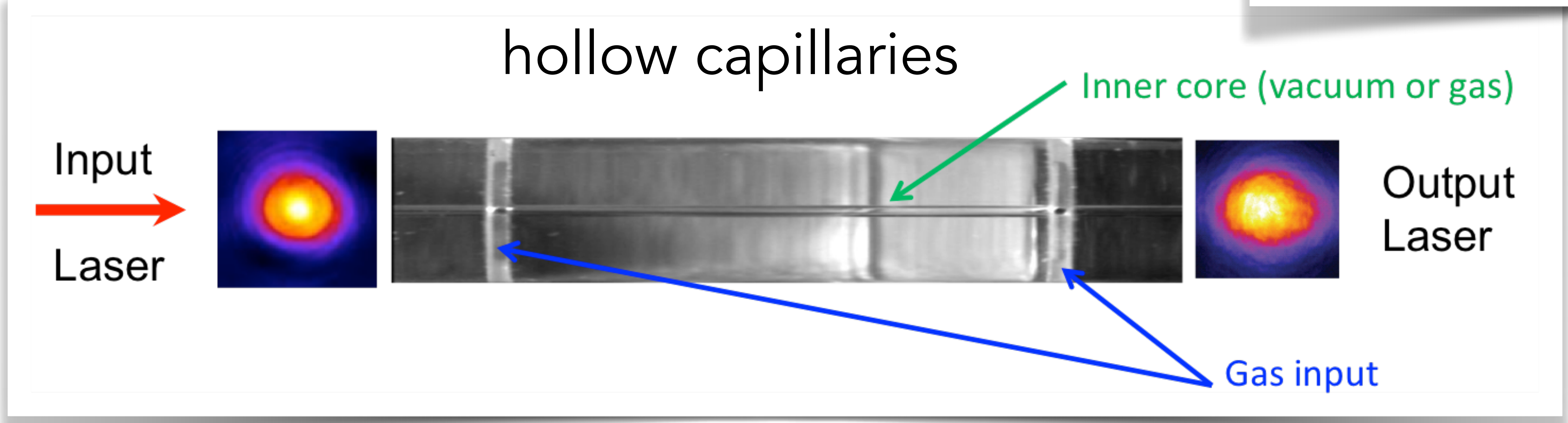
A wide variety of plasma sources has been used

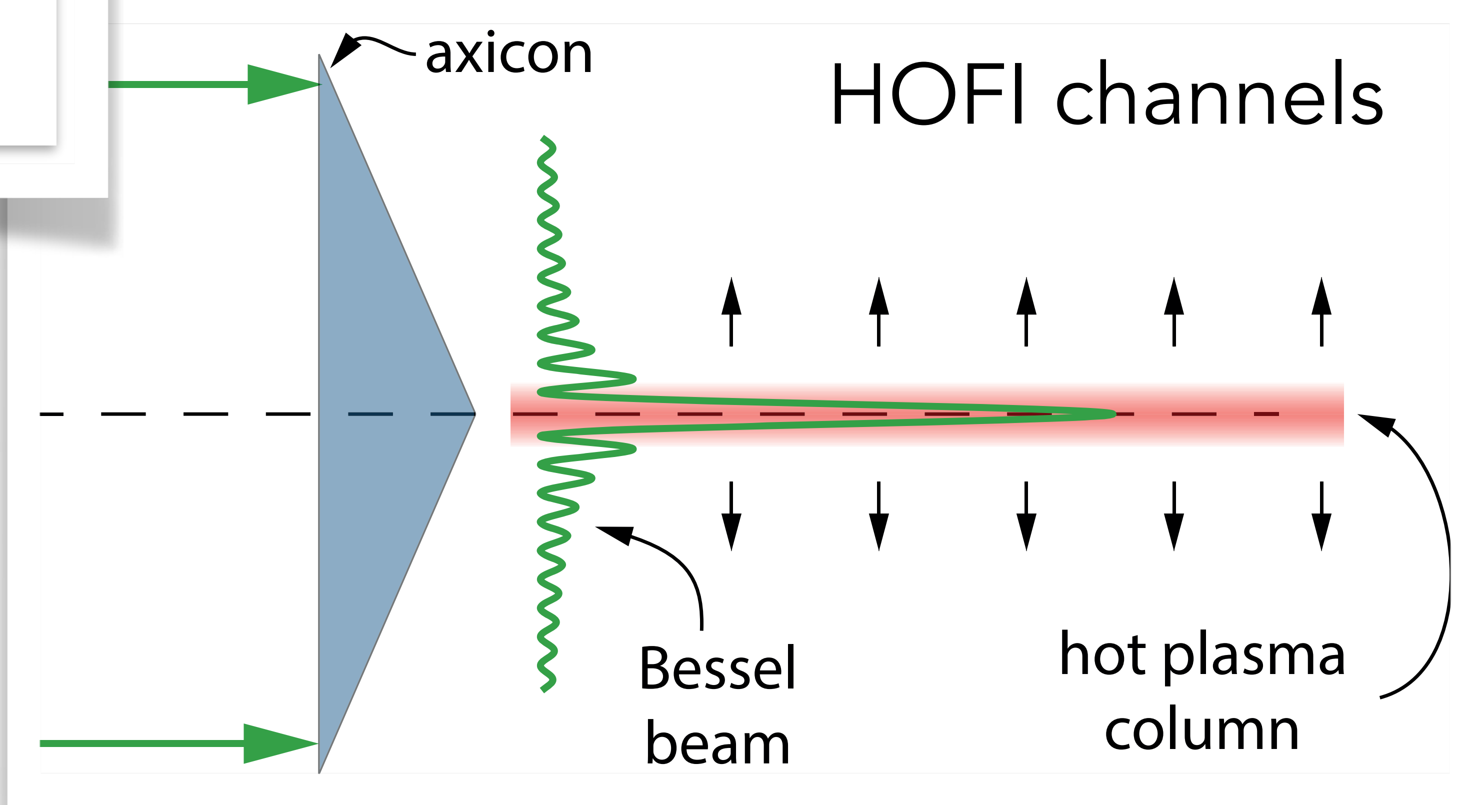








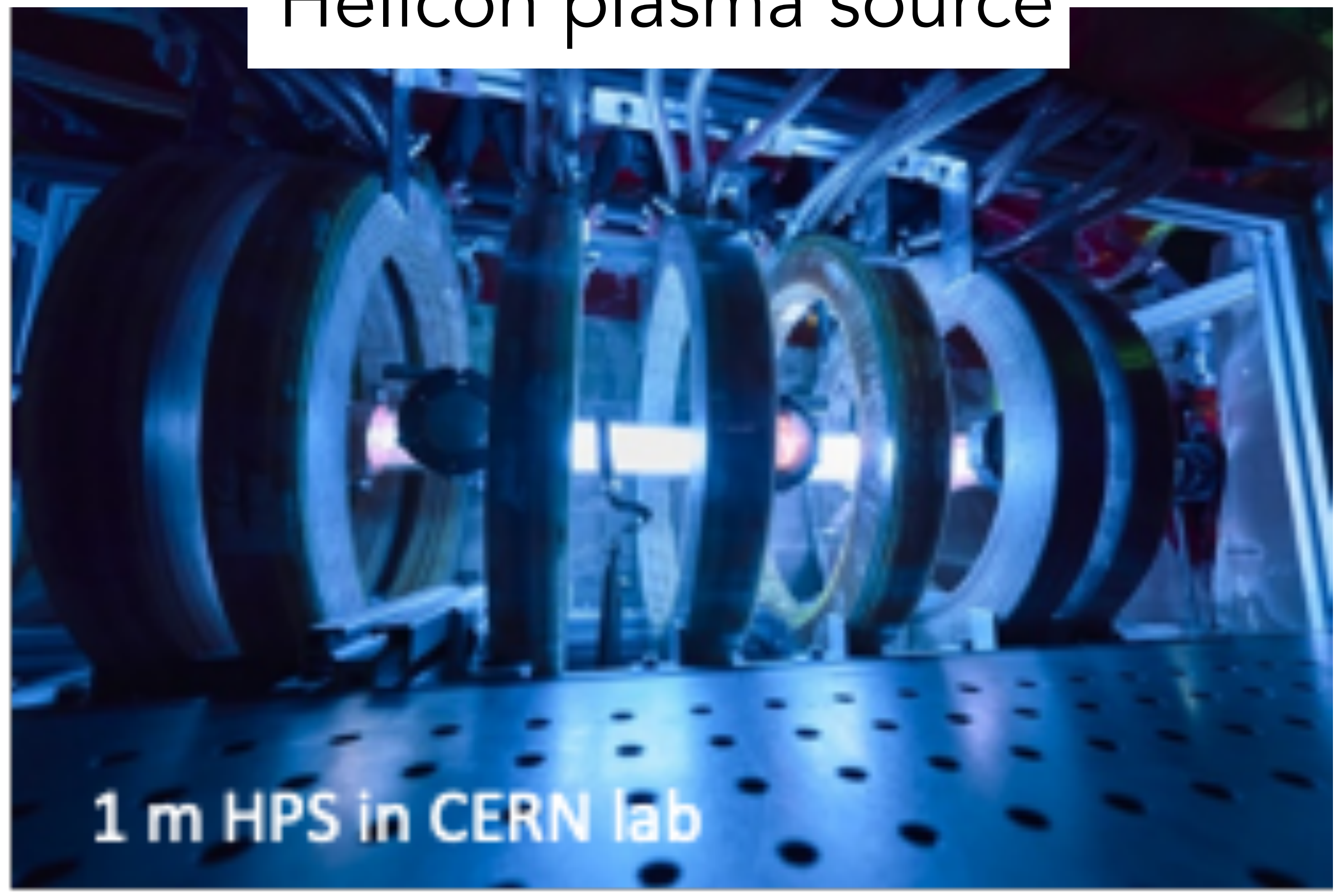




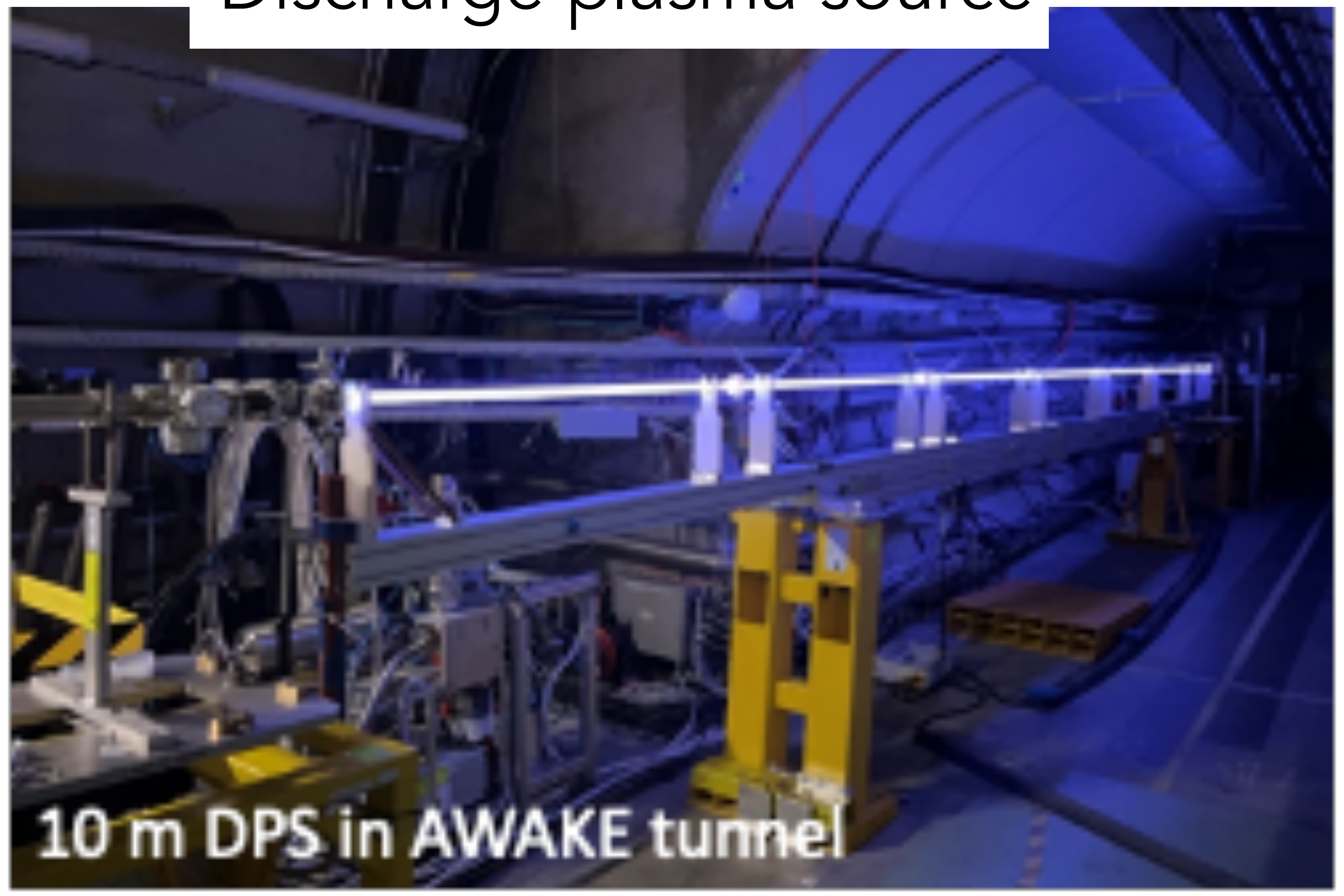
Plasma sources for AWAKE

- AWAKE Run 2 plasma source:
  - Baseline: 10 m Rb vapour source ionized by TW laser
  - Limitation: laser pulse intensity depletion for length > 10 m
- Also investigating discharge sources:
  - Dedicated plasma source labs at CERN
  - 5 collaborating institutes
  - Addressing challenges of density, uniformity, reproducibility, scalability
- Helicon plasma source
  - RF wave heated plasma, pulsed 10 Hz rep. rate
- Discharge plasma source
  - Pulsed-DC discharge, 1 Hz rep-rate

Helicon plasma source

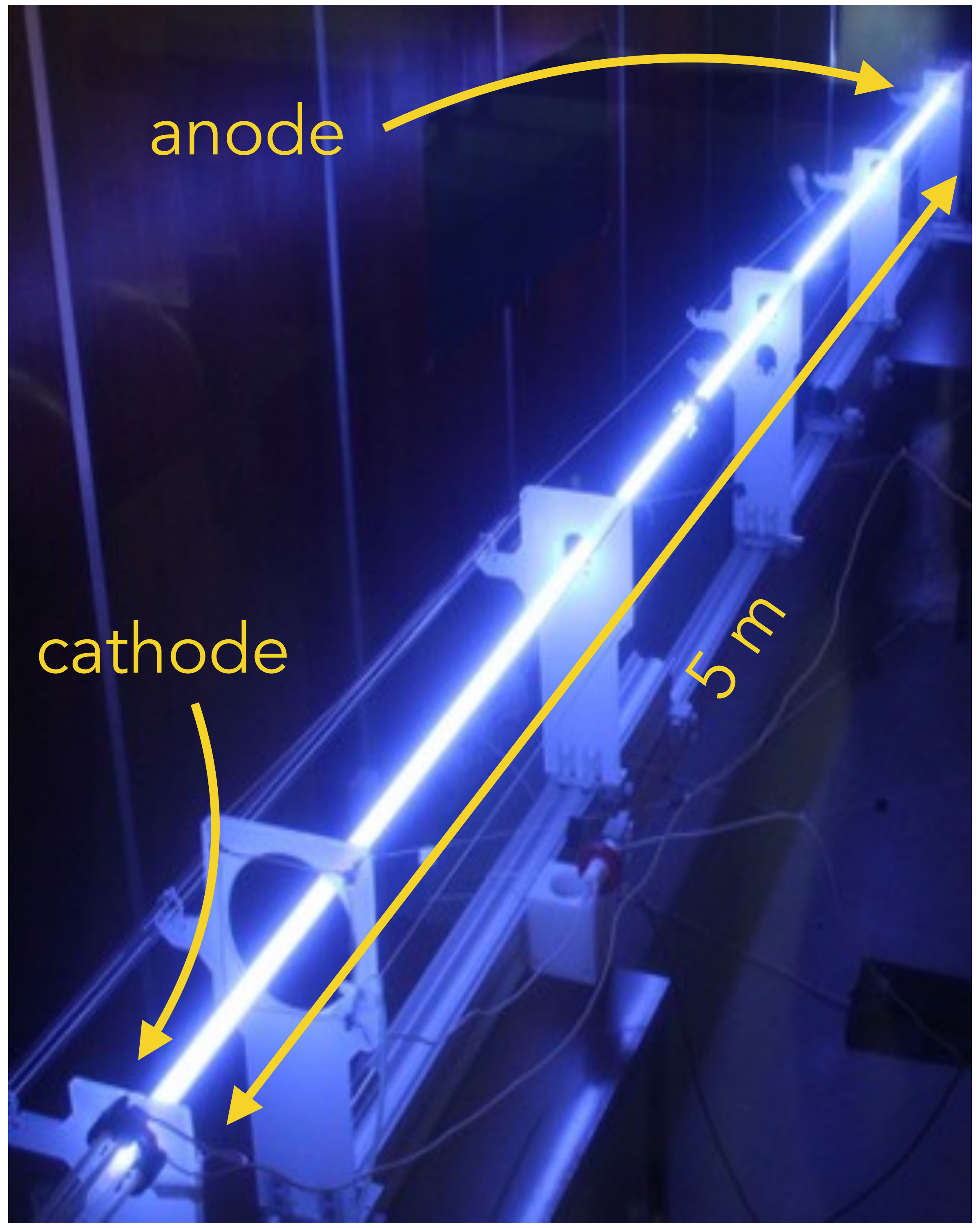


Discharge plasma source



Plasma sources for AWAKE: Discharge sources

- Plasma for AWAKE Experiment
  - Length scalable 1 m to few km
  - Plasma density 1-10 x 10^{14} cm^{-3} uniformity/reproducibility/ control ~0.1%
  - heavy ions (≥ Argon)
- Solution [1]
  - Sequence of Direct Current Cold Cathode Discharges with
  - … Common Cathodes and Anodes and
  - … Current Balancing
  - … with high-Voltage ignition + high-current precise plasma heating [2]
- Prototypes of single and double plasmas (with common cathode)
  - Demonstrated up to 10 m length [3]
  - 3 to 10 m long plasmas, Helium to Xenon self-modulated 400 GeV proton bunches in AWAKE (2023) [3,4,5]



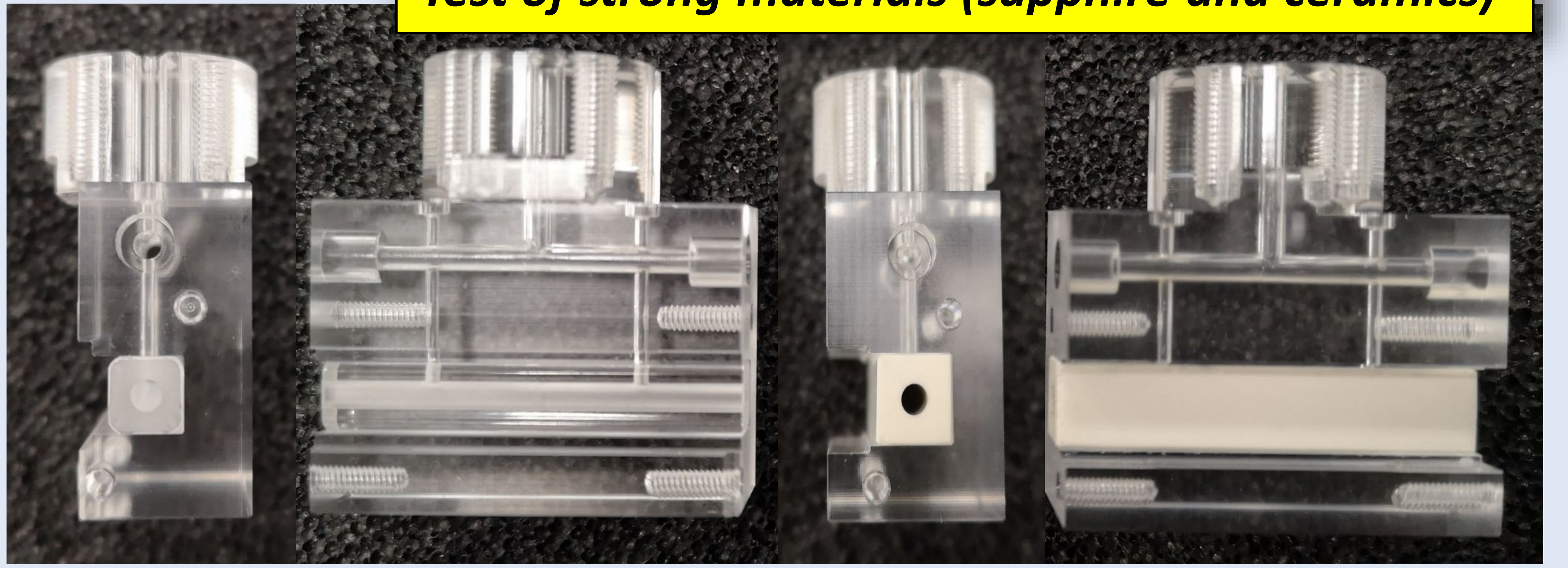
[1] N. C. Lopes et al. in preparation
[2] N. Torrado et al. IEEE Trans. Plas. Sci. doi: 10.1109/TPS.2023.3337314
[3] C. Amoedo et al. in preparation
[4] L. Verra et al. in preparation
[5] M. Turner et al. in preparation

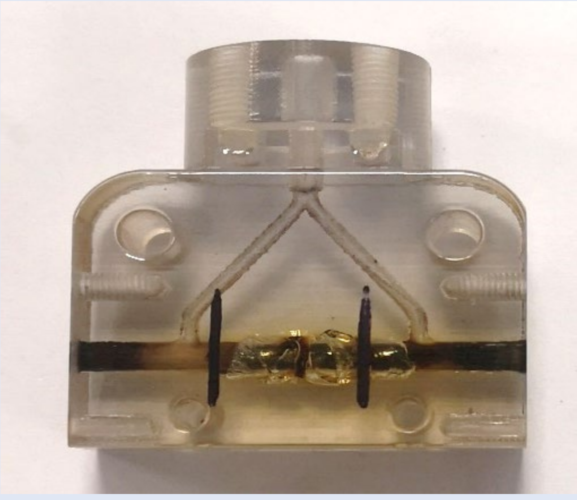
To operate at high repetition rate the key point is the thermal dissipation

1. Solid-state high repetition-rate discharge system
2. Strong materials capable of dissipating thermal energy
3. Vacuum systems suitable for continuous flow gas injection (turbo and primary pumps cooling system)

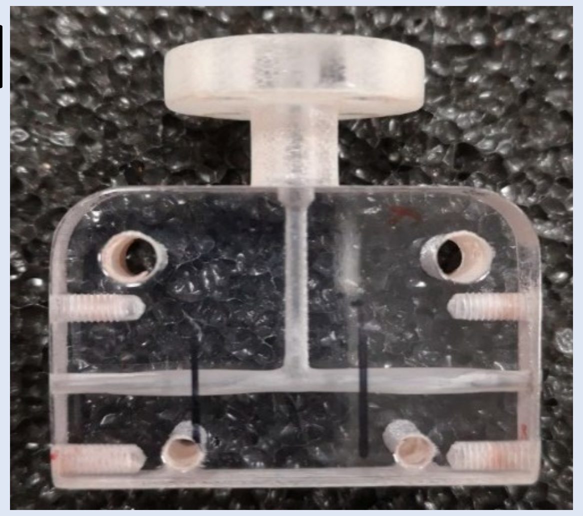
2.

Test of strong materials (sapphire and ceramics)





High repRATE can cause a rapid degradation of unsuitable soft materials



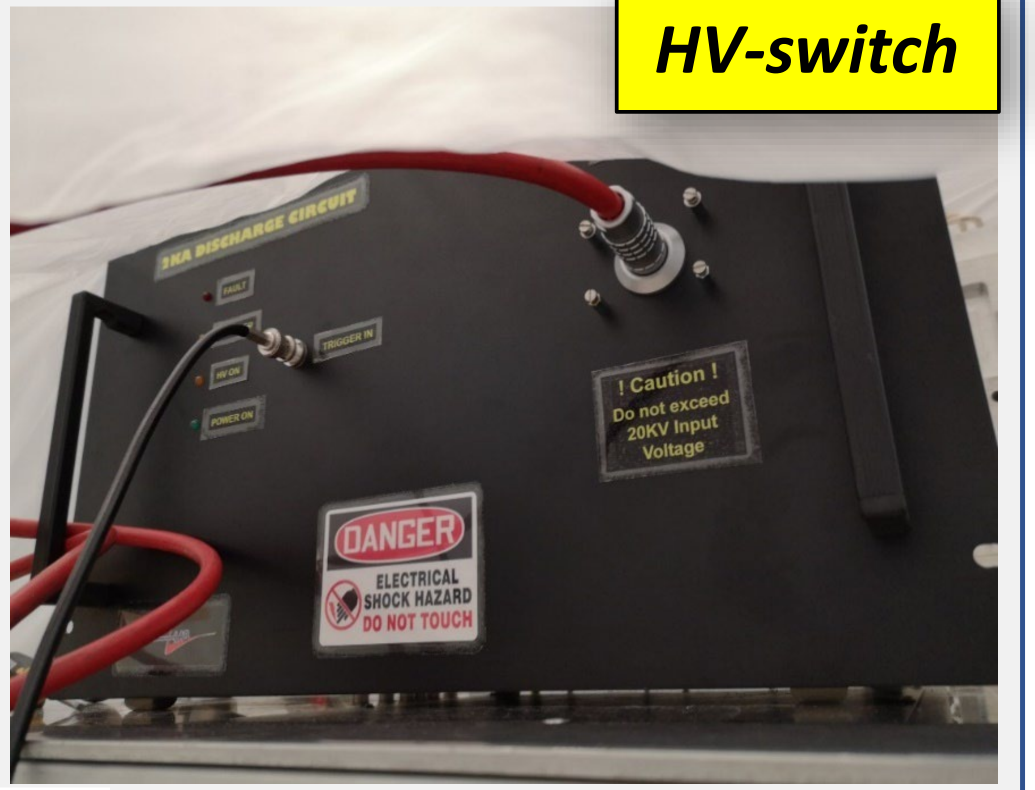
1.

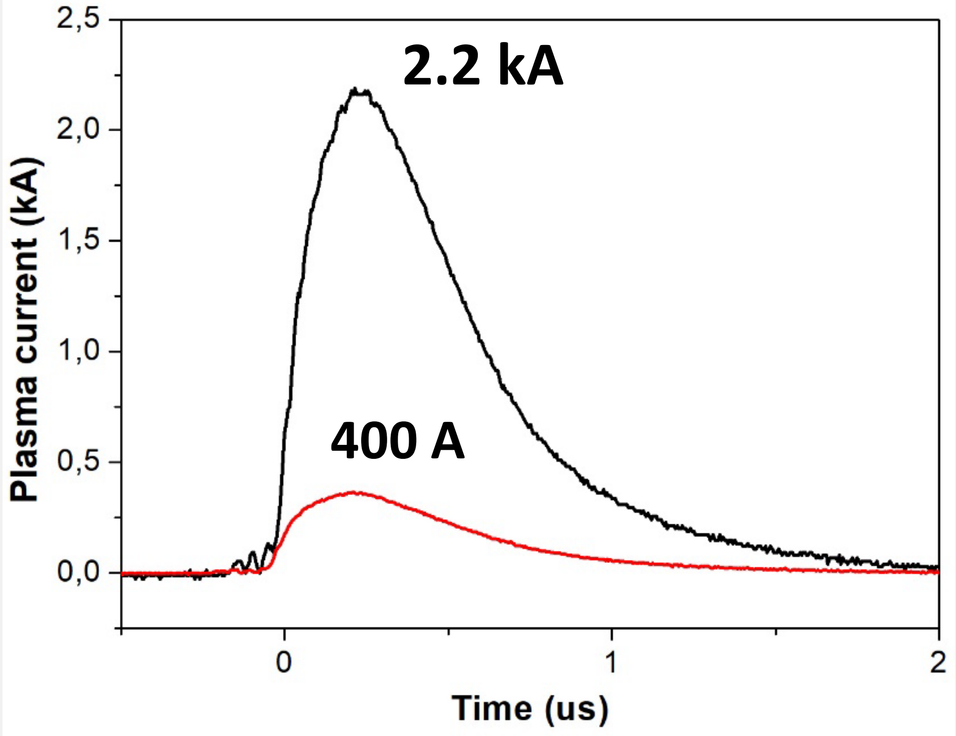
High voltage for plasma formation
High current output for high repRATE

HV- generator
25 kV
20-200 mA

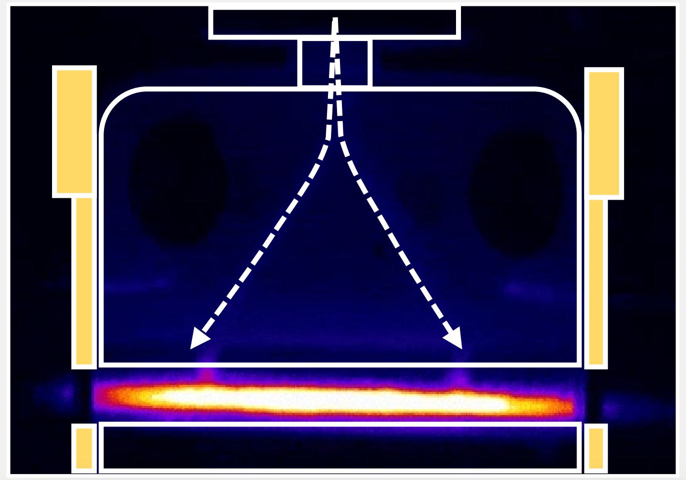
Thermal dissipation of components is crucial

HV-switch





Current pulses from 100 to 2500 A at repetition rate from 1 to 400 Hz



Discharge capillary

Angelo.Biagioni@lnf.infn.it

High repetition rate capillary discharge for EuPRAXIA

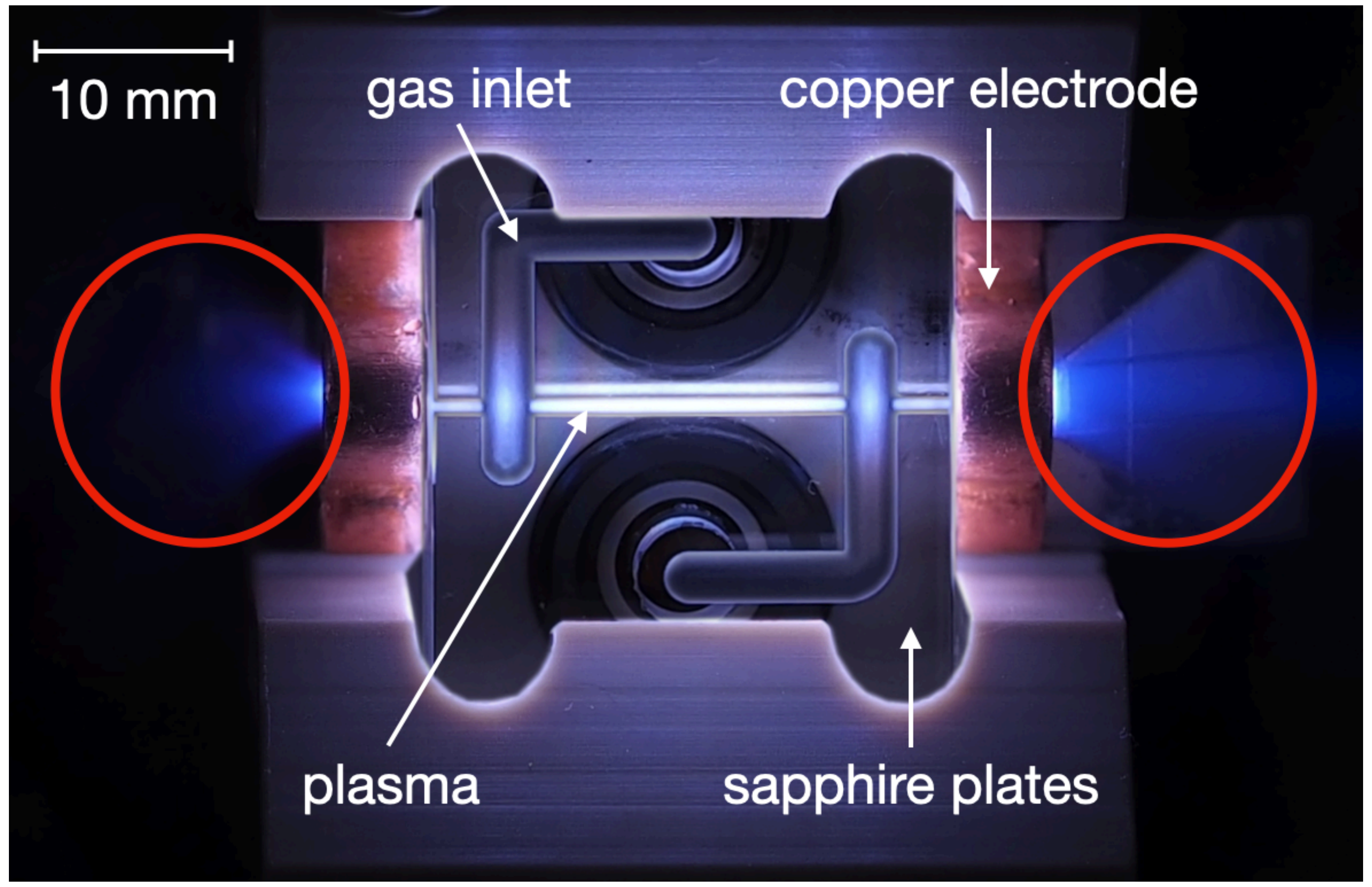
Capillary discharge operating at 50 Hz

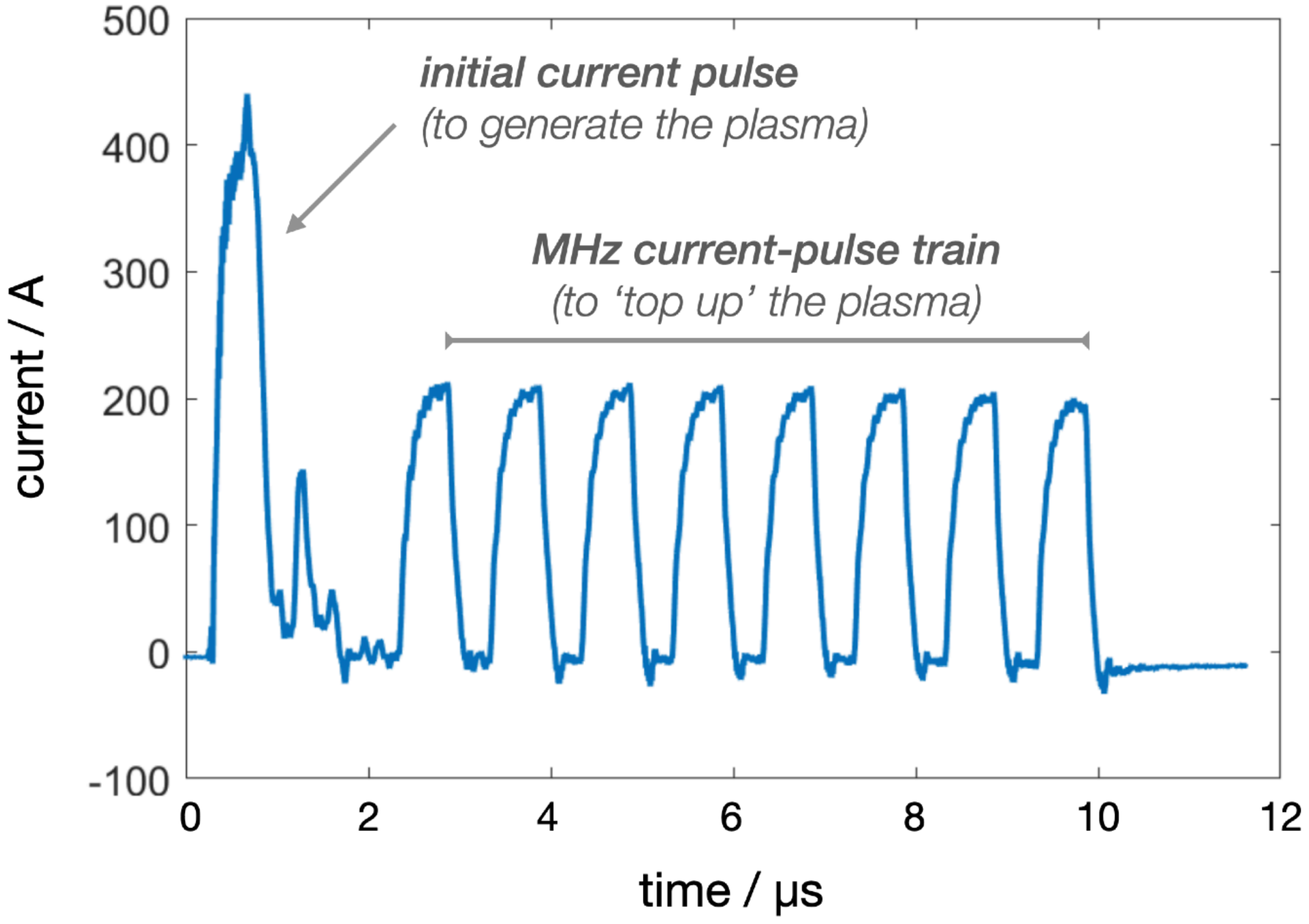
High repetition rate capillary discharge for EuPRAXIA

Capillary discharge operating at 50 Hz

Plasma sources for HALHF/FLASHForward: high repetition rate (MHz)

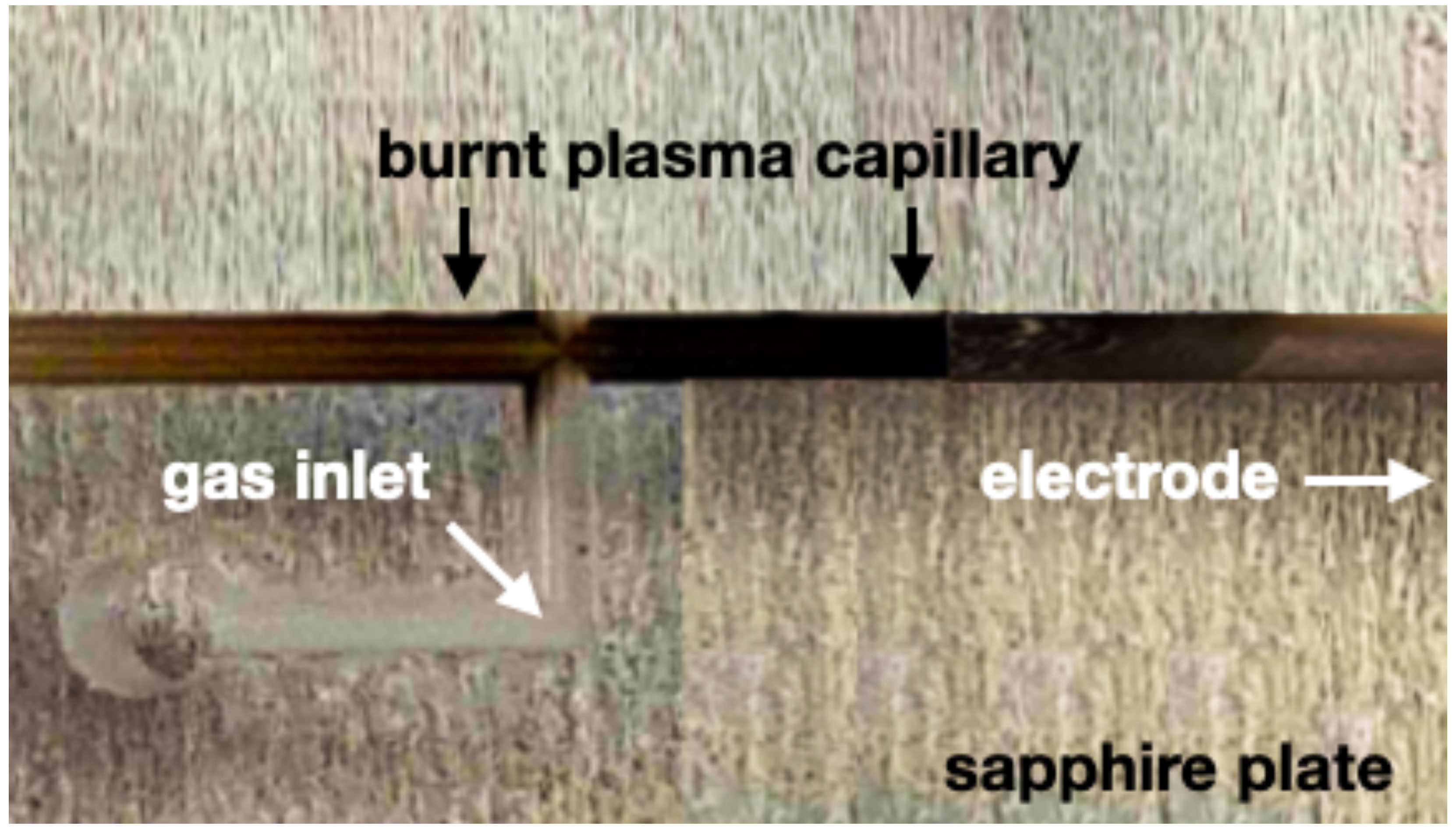
- MHz operation is required for all burst-mode RF accelerators
  - Likely required for HALHF
  - Certainly needed for some FELs e.g. FLASHForward, XFEL
- Plasma lives on the μs timescale ➞ must massage what still exists to approximately the same state
  - Limit expulsion ➞ geometry changes
  - Counteract recombination…
- FLASHForward has driven the development of a MHz discharge system
  - Based on solid-state technology

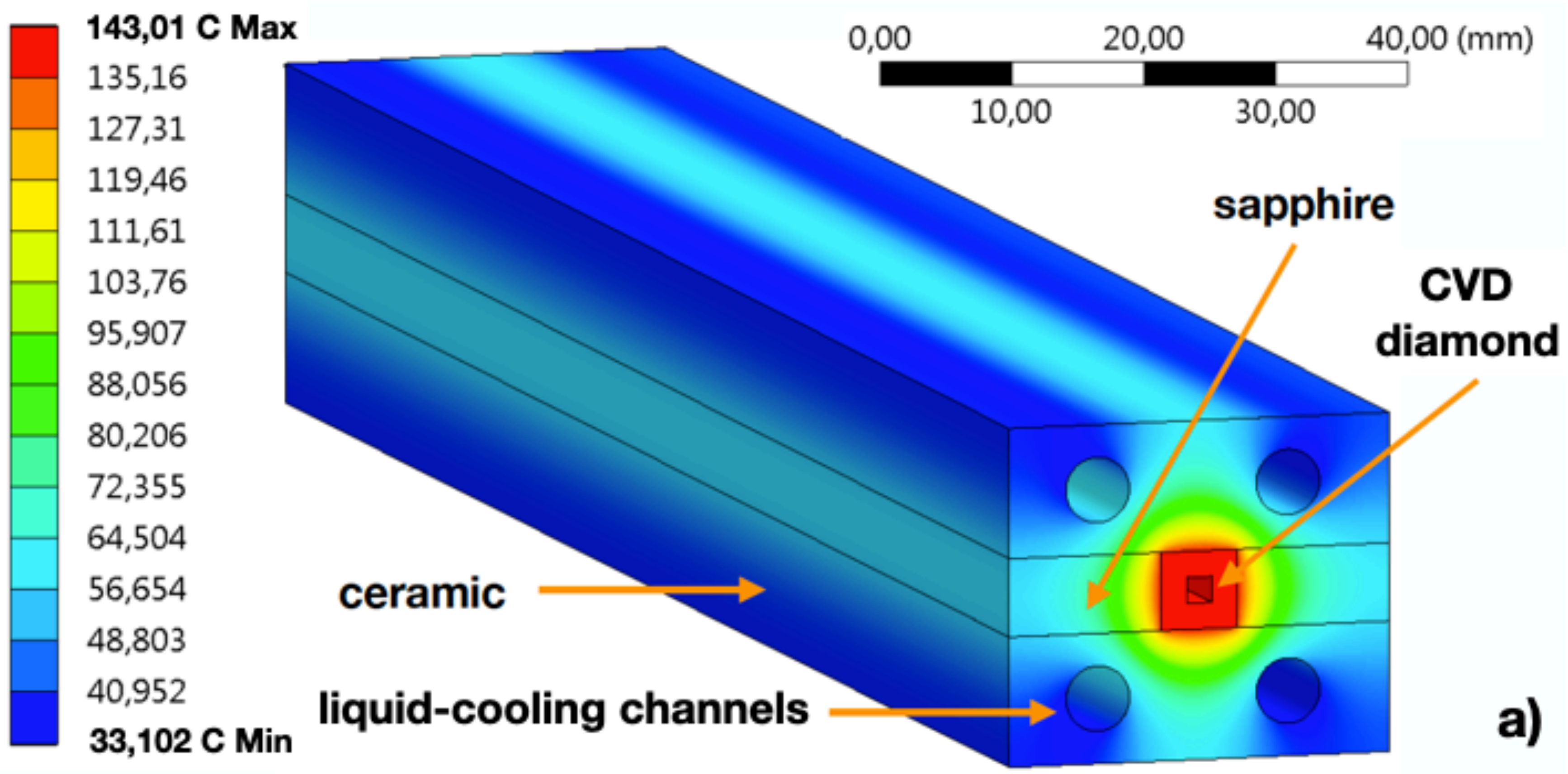




Plasma sources for HALHF/FLASHForward: high average power (10 kW/m)

- Current discharge-capillary technology operates with power gradients of ~5 W/m
- … yet heating/burning of the capillaries is evident after tens of thousands of shots
- HALHF and FEL plasma boosters must survive millions of shots with ***O***(10 kW/m) power gradients
  - Orders of magnitude beyond the state of the art
- Many technological developments needed:
  - Novel plasma-source designs
  - Robust materials e.g. grown polycrystalline diamond (previously used at BELLA)
  - Active (liquid) temperature stabilisation





All-optical plasma channels

Durfee & Milchberg, Phys Rev. Lett. 71 2409 (1993)
Volbeyn et al. Phys. Plas. 6 2269 (1999)
Lemos *et al.*, *POP* **20** 063102 (2013),
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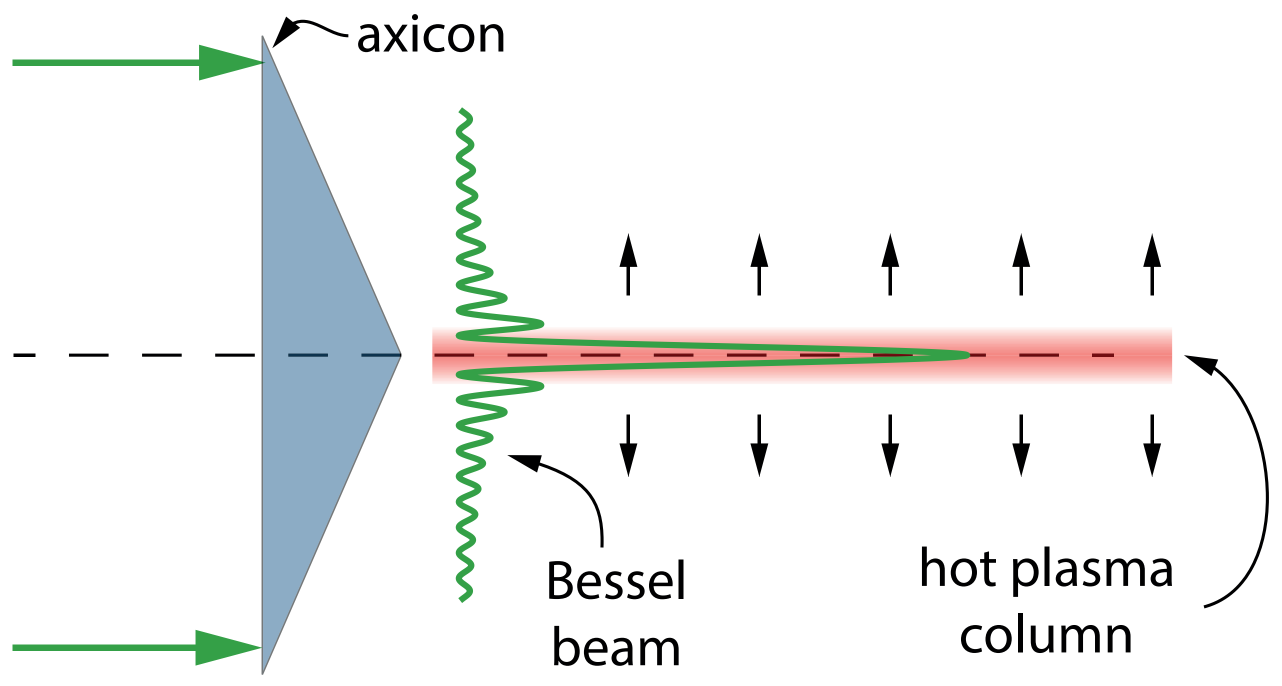
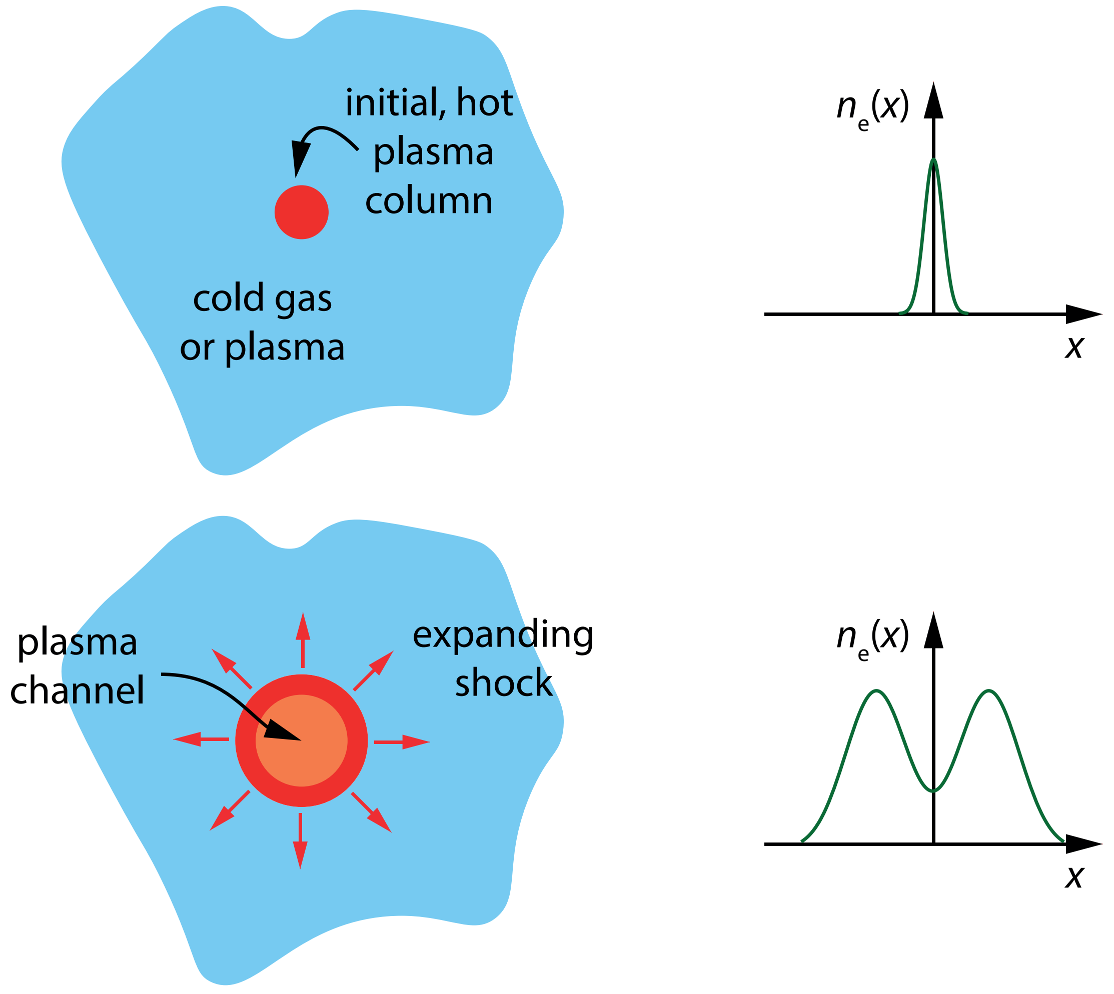
R.J. Shalloo et al. Phys Rev E 97 053203 (2018)

- Create & heat column of hot plasma
- Expansion into surrounding cold gas / plasma drives cylindrical blast wave
- Plasma channel formed within expanding shell
- Attractive for high rep rate since free-standing and "indestructible"
- Collisional ionization(I ~ 10^{14} W cm^{-2}) limits channels to high density n_e > 10^{18} cm^{-3}
- Optical field ionization (I ~ 10^{16} W cm^{-2}) is density independent ⇒ low density channels n_e << 10^{18} cm^{-3}





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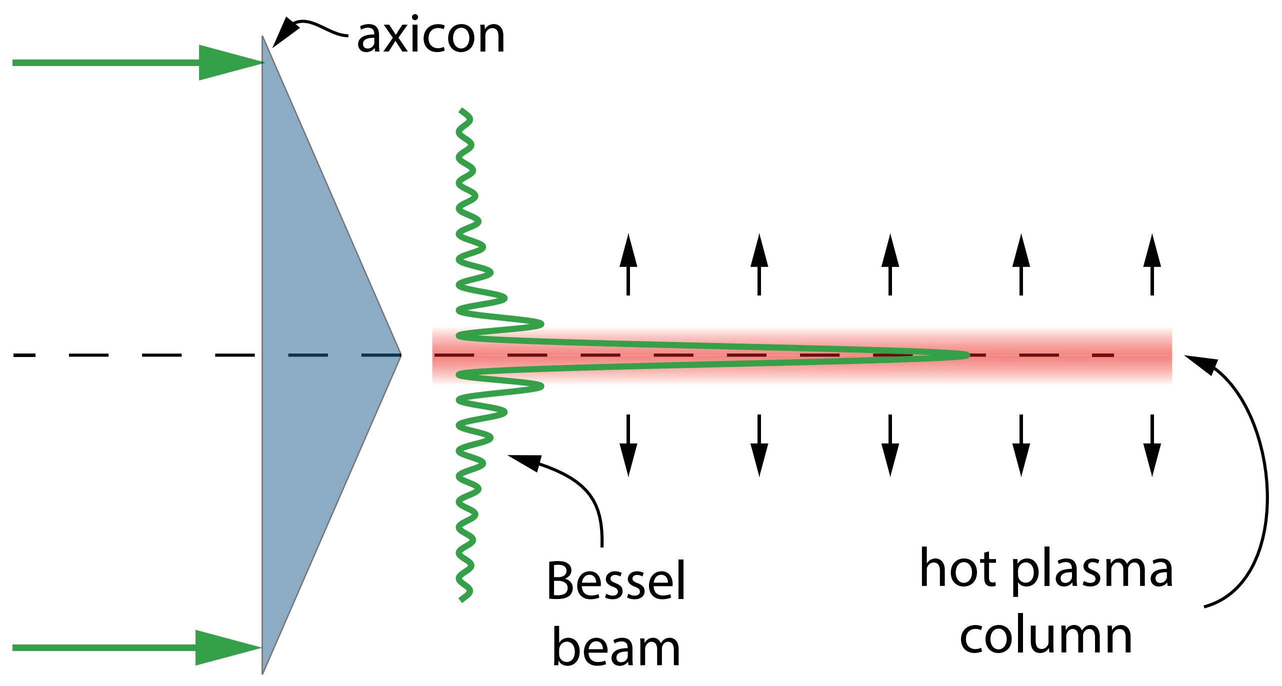
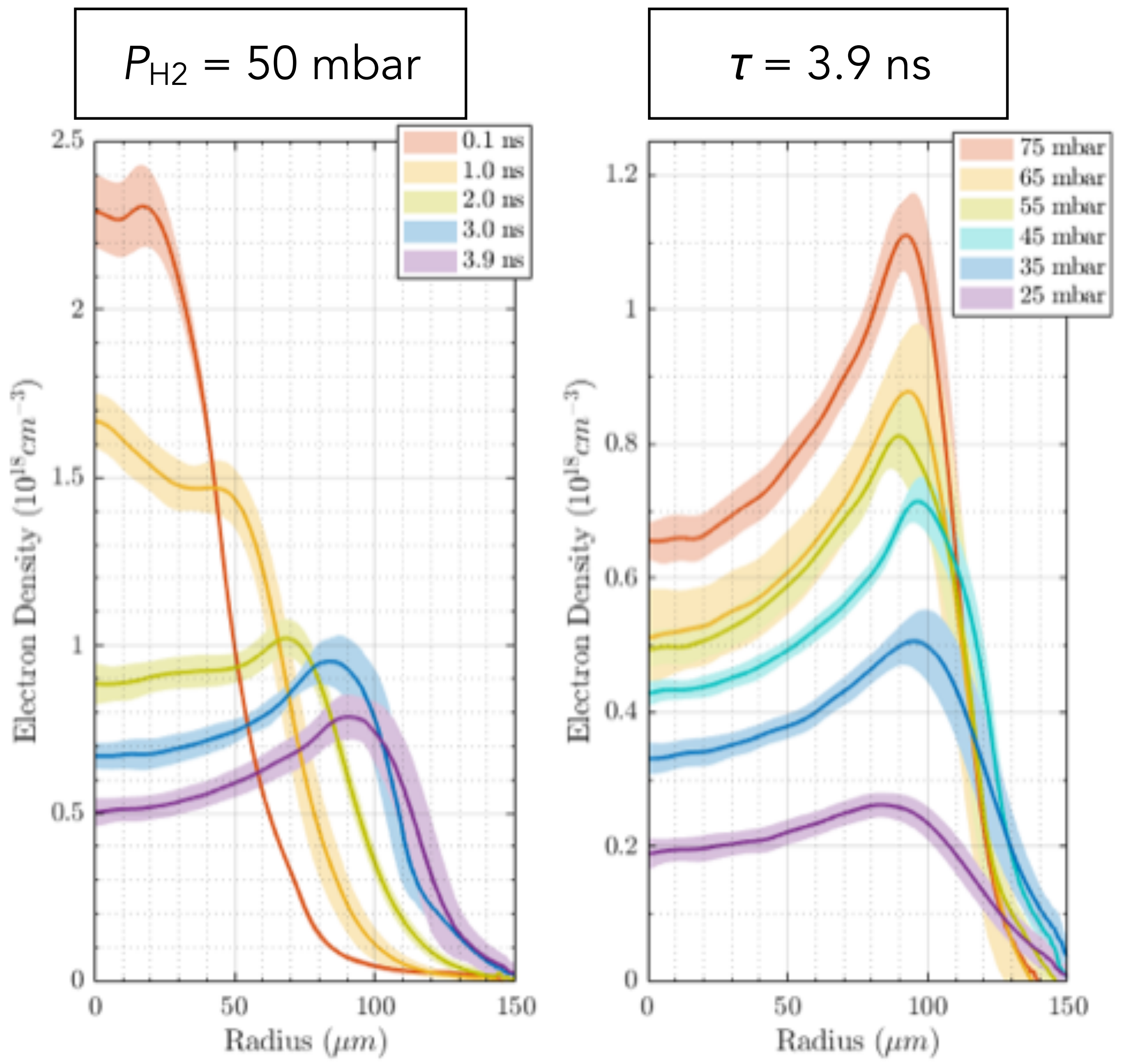
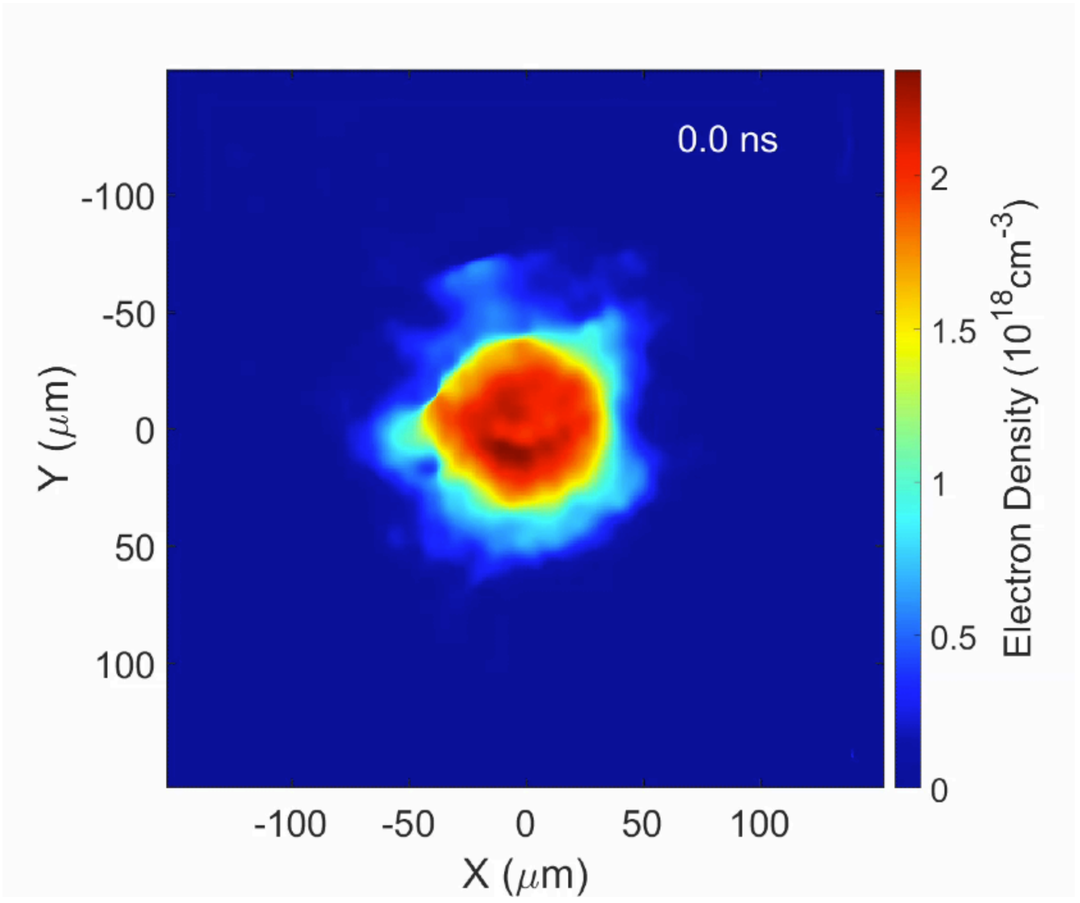


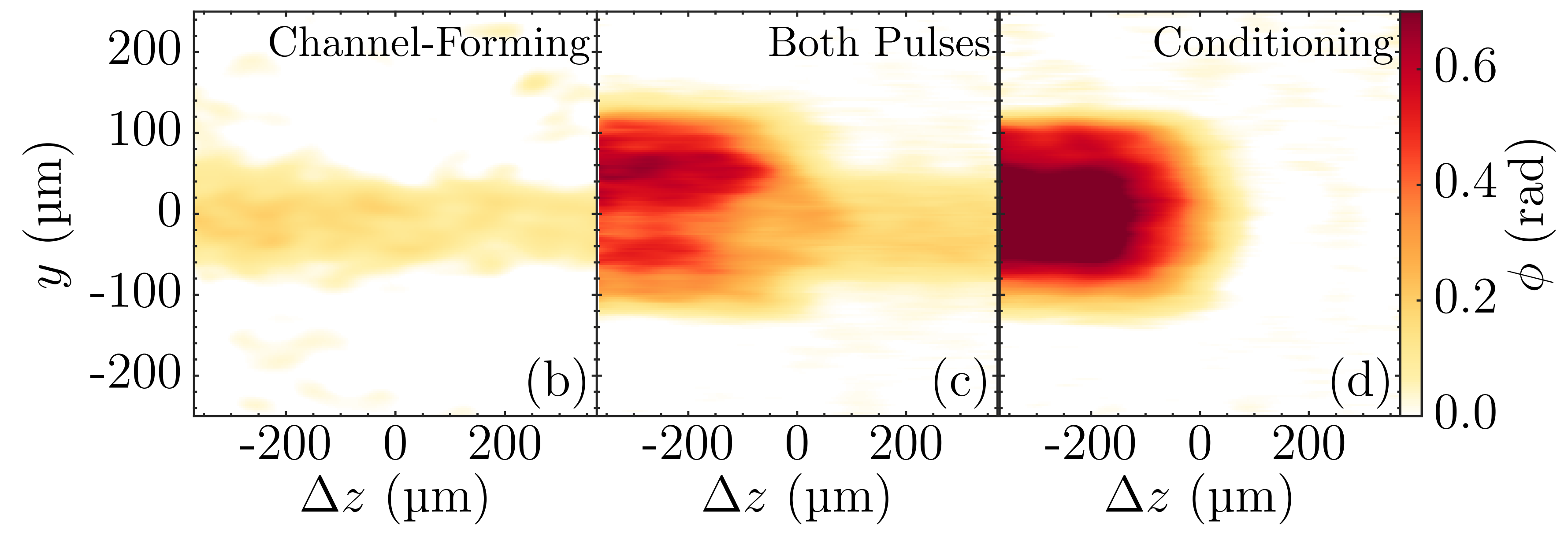
E_L:	27 mJ
τ:	50 fs
Poln:	Circular

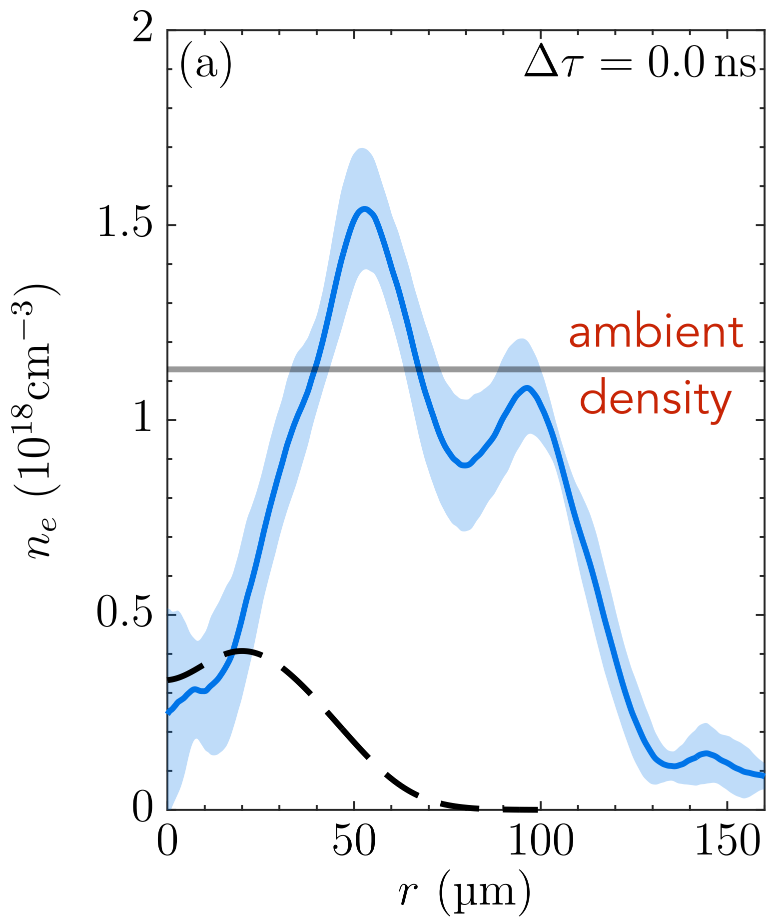


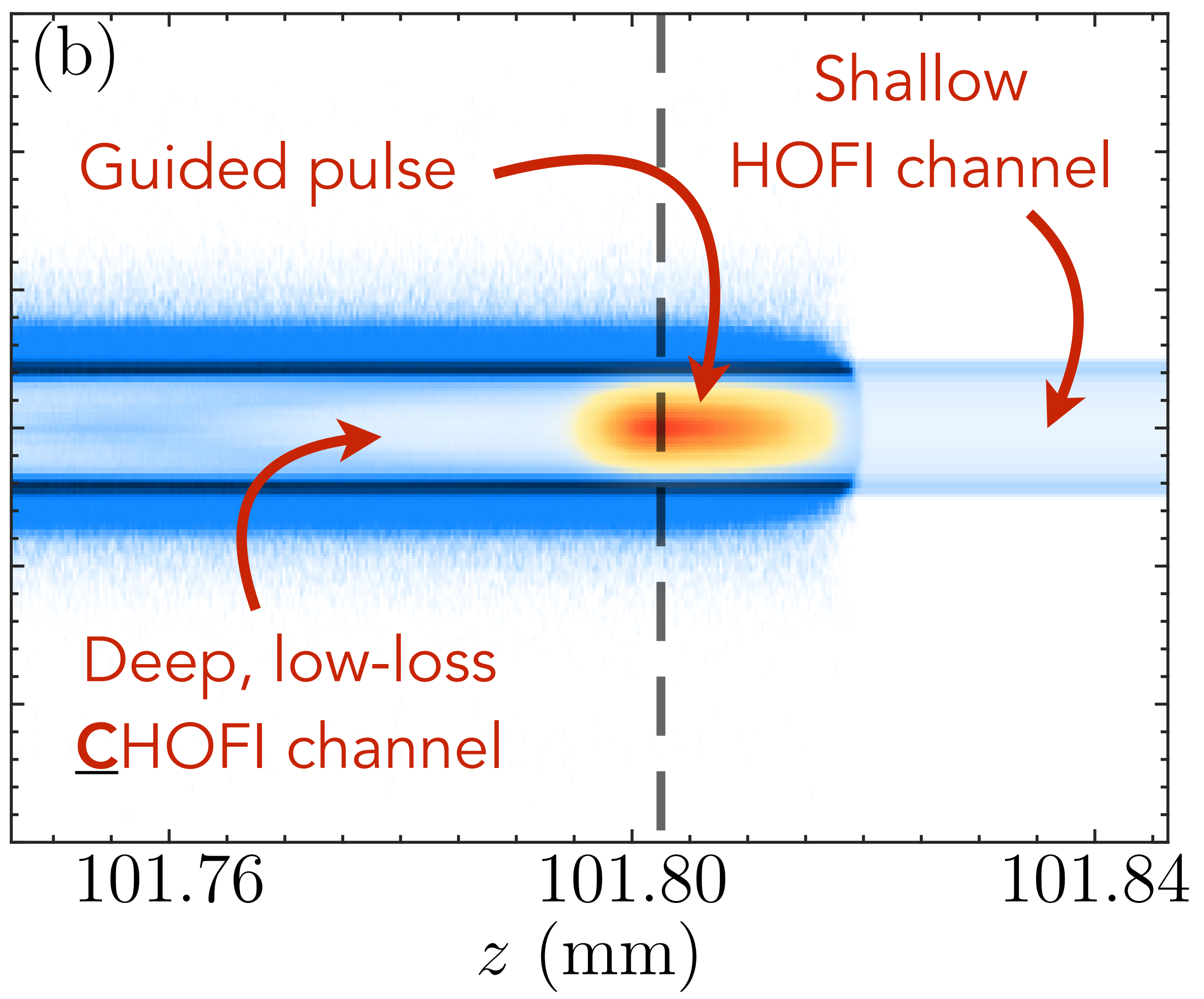


Conditioned HOFI channels

D. Spence & S. M. Hooker, *J. Opt. Soc. Am. B* **17** 1565 (2000)
R.J. Shalloo et al. *Phys Rev Accel. Beam* **22** 41302 (2019)
A. Picksley et al. *Phys Rev E* **102** 053201 (2020)
L. Feder et al. *Phys Rev Res* **2** 043173 (2020)
B. Maio et al. *Phys Rev Lett* **125** 074801 (2020)

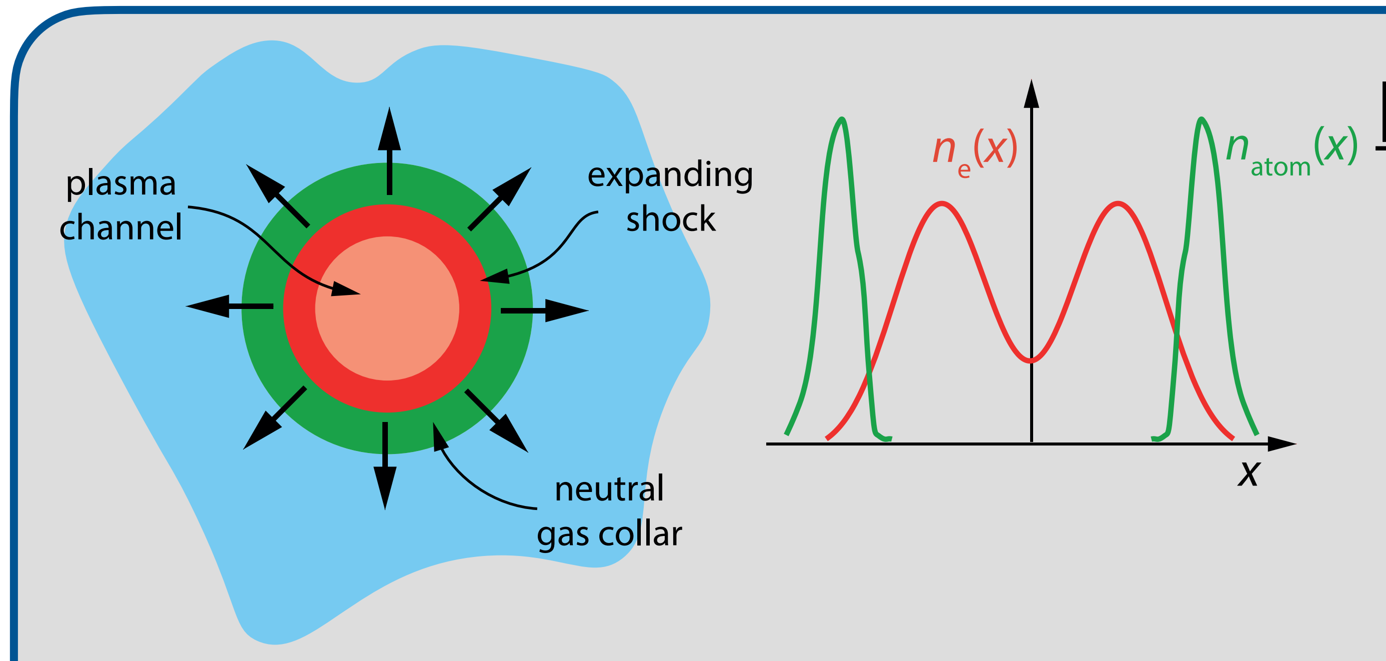






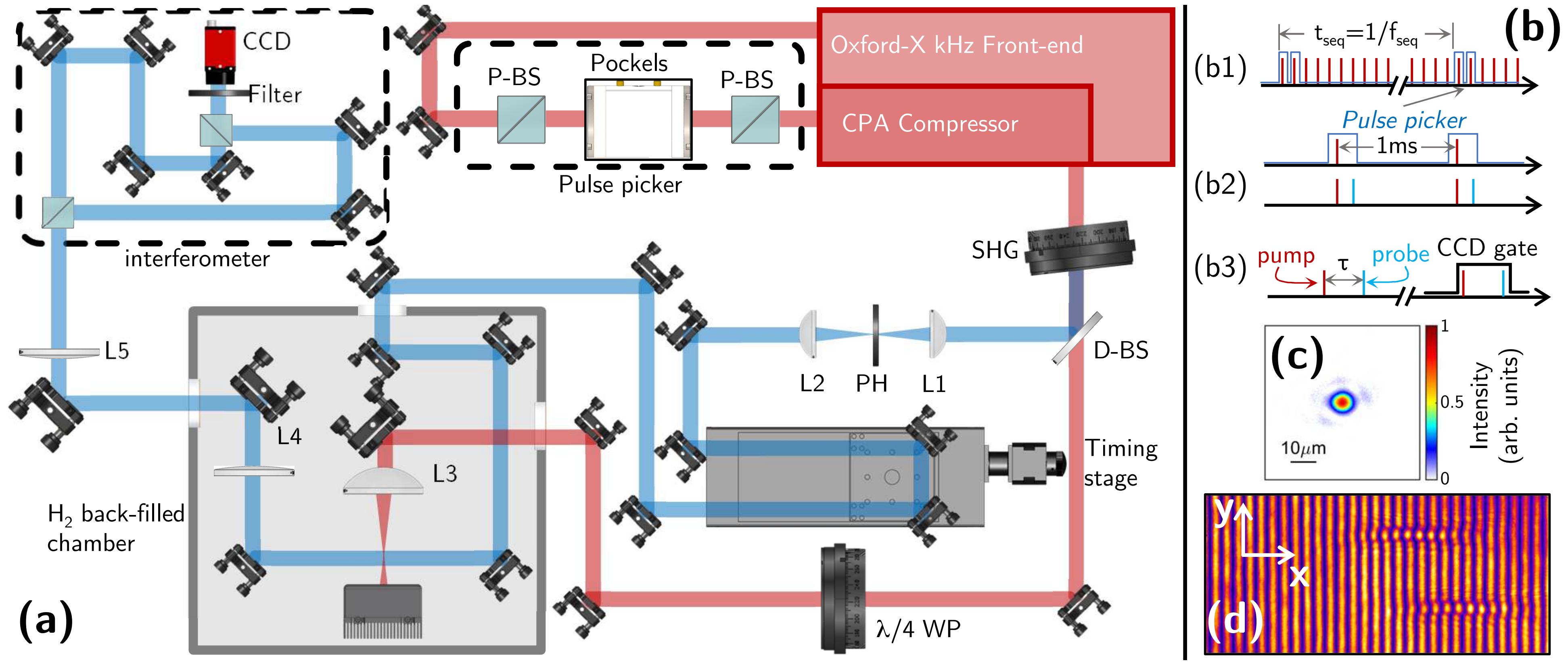
- Power attenuation length of CHOFI channel is L_{att} > 20 m!

Mechanism

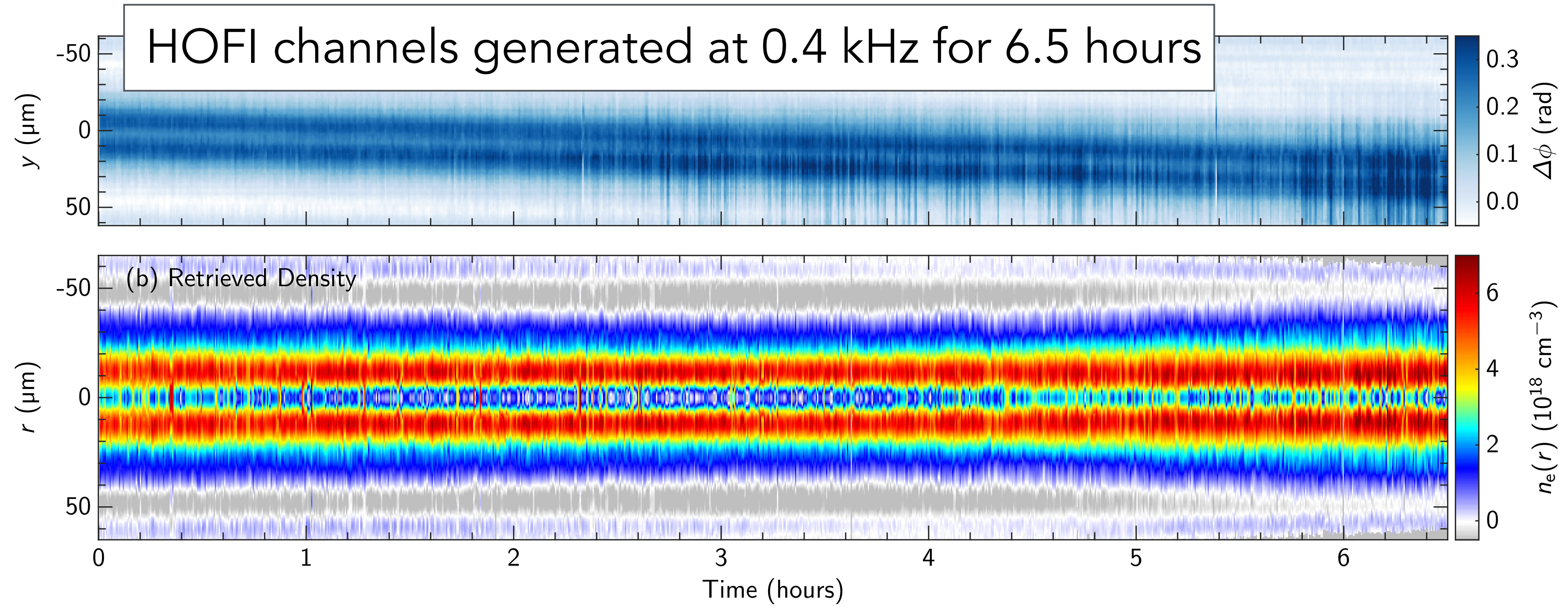


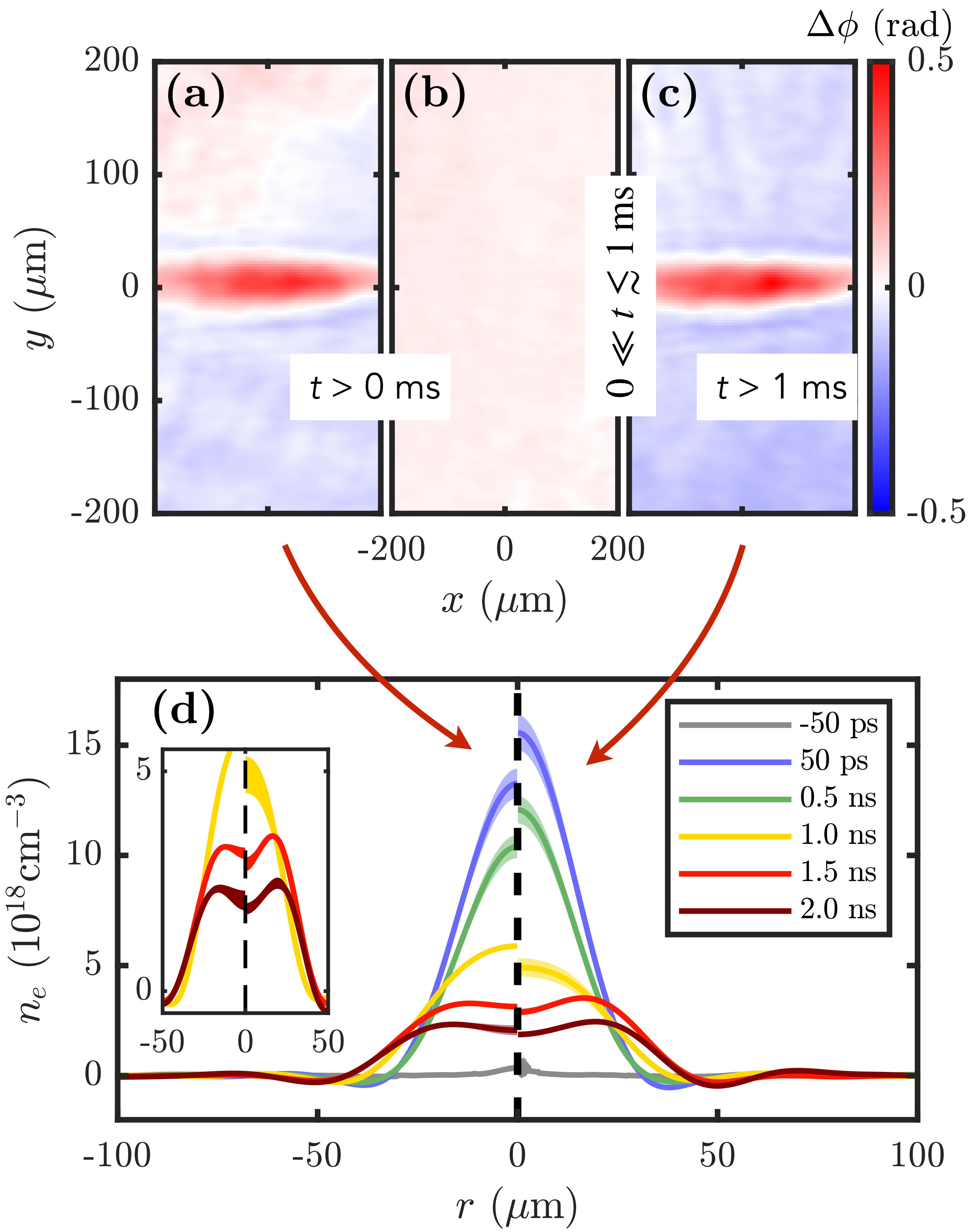
- Two-colour interferometry experiments by Milchberg group show collar of neutral gas pushed out by initial shock
- Collar ionized by transverse wings of guided / conditioning pulse
- Can also use high-order Bessel beam to condition the HOFI channel

Operation of HOFI channels at kHz rep. rate



A. Alejo *et al. Phys Rev Acc. Beams* **25** 011301 (2022)





- Generated HOFI channels at 0.4 kHz for 6.5 hours with no degradation of channel properties or optics

Summary

- Operating plasma accelerators at high repetition rates presents formidable challenges for the plasma source (as well as for the driver)
- Plasma recovery time (~ 100 ns?) allows high (> 1 MHz ?) operation in principle…
- … but still need to develop systems capable of handling very high mean power deposition
- Further work is required on:
  - Better understanding of the physics of "plasma recovery"
  - Modelling of gas & plasma flow
  - Development of systems for moving gas in / out of the accelerator stage
  - High repetition rate discharges
  - Energy recovery schemes
  - Simulations of plasma recovery over ~ 100 ns timescale
- What is needed?
  - Identification of common goals and areas of collaboration
  - Additional expertise (engineers,…)
  - Funding!