Plasma Source for High-Repetition Rate (and high average power)

Involved Issues

Lucas Schaper for the FLASH>> team
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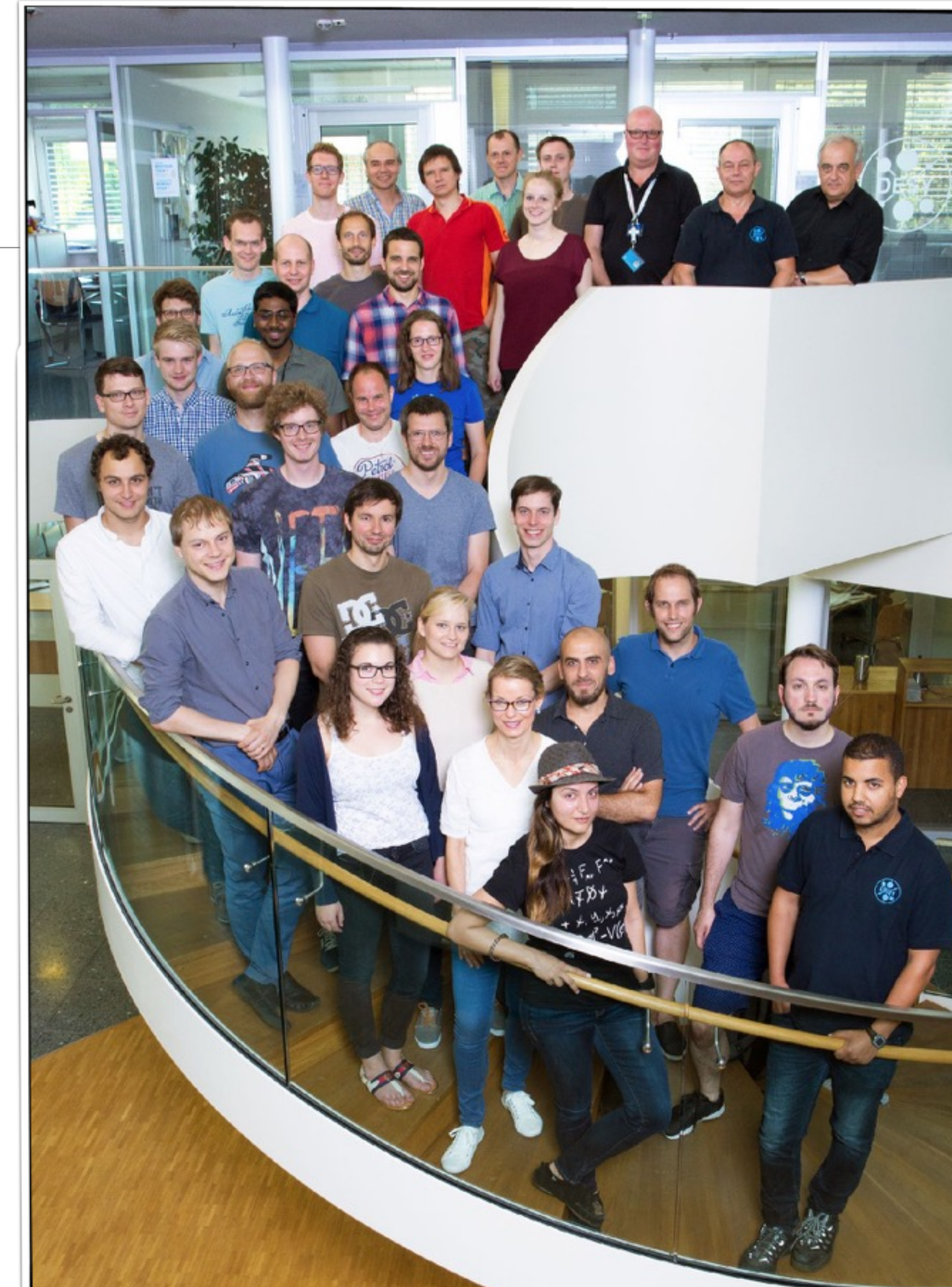
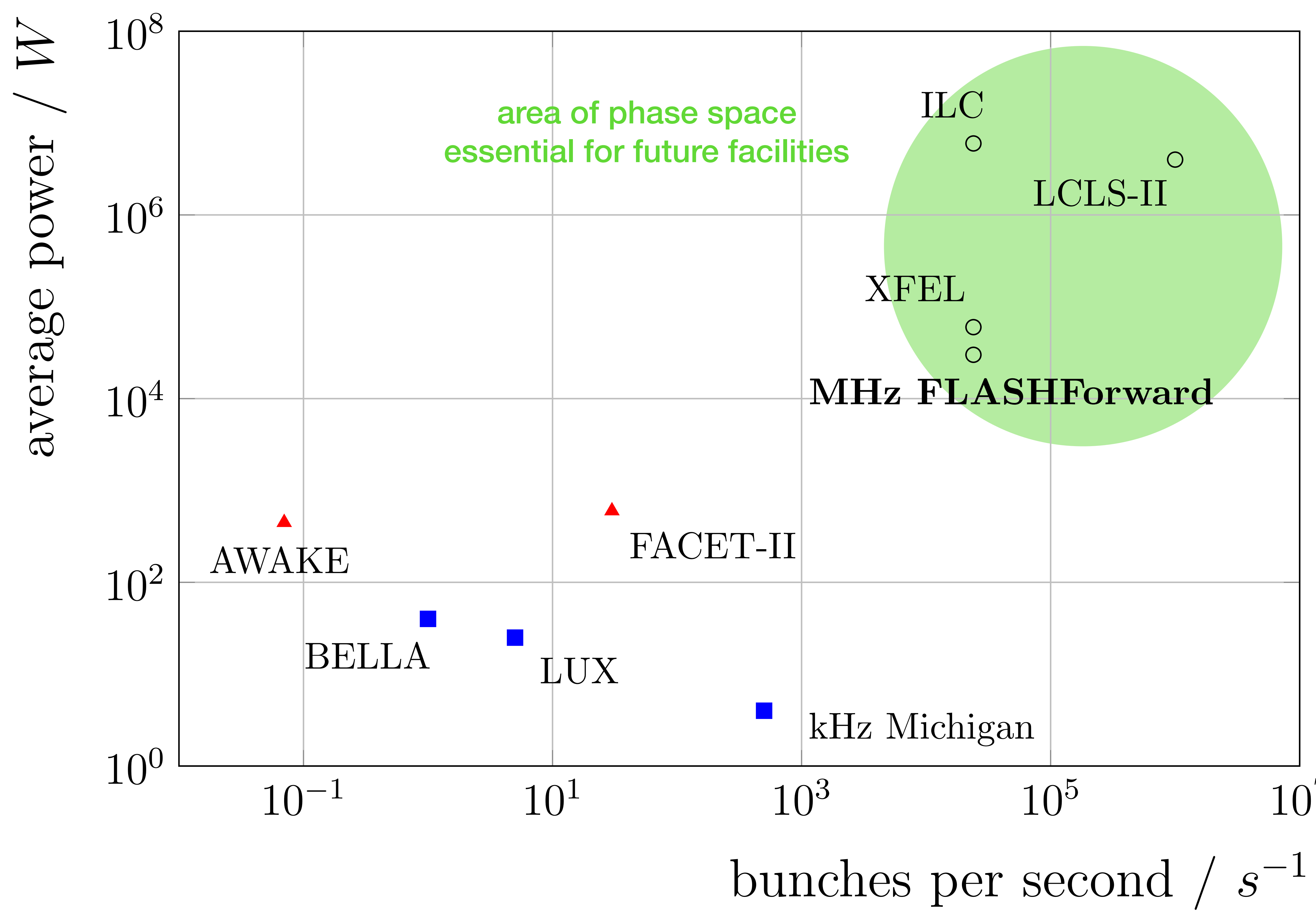


Motivation

- Almost all existing and upcoming L / PWFA machines restricted to operation of repetition rate below 100 Hz and average power below 1kW
- state of the art SRF based accelerators are above 10 kHz and 10kW
- FLASHForward experiment allows to extend both regimes, repetition rate and average power
    - Bunch rep rate up to 3 MHz
    - current avg power of 60W, limited by temporary beam dump

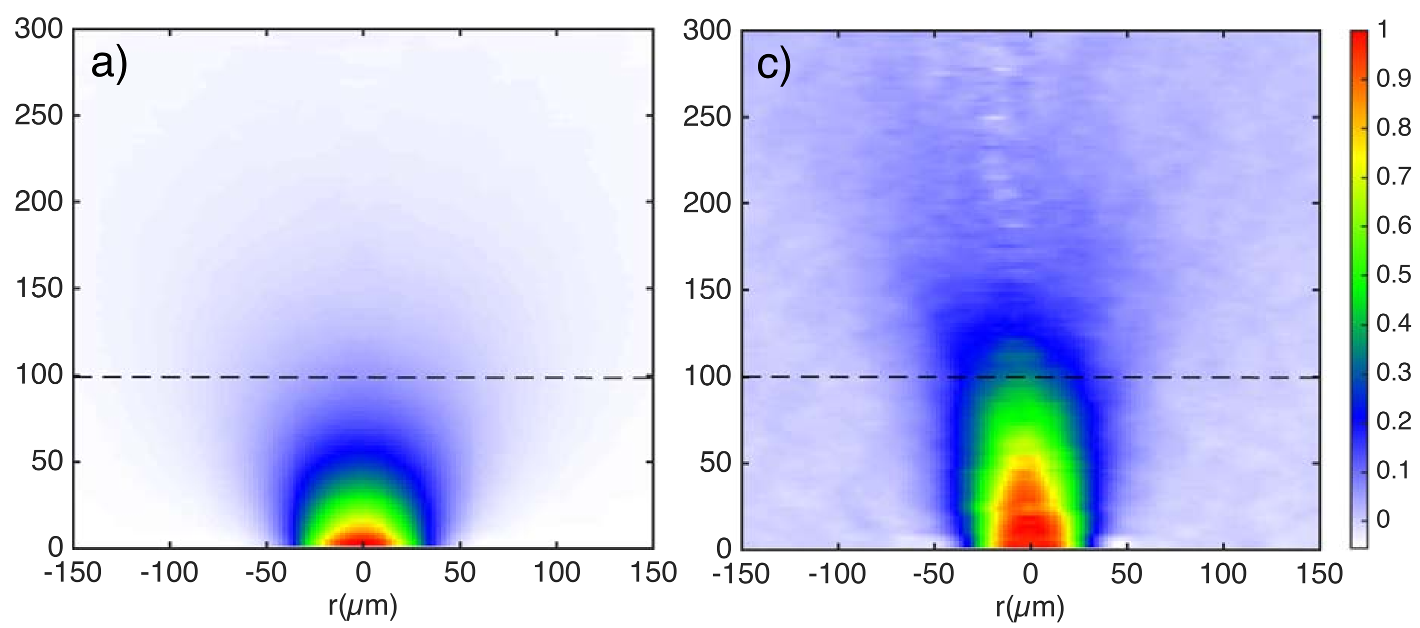
See presentation Wednesday 14:10 on FLASH>> by Richard D'Arcy

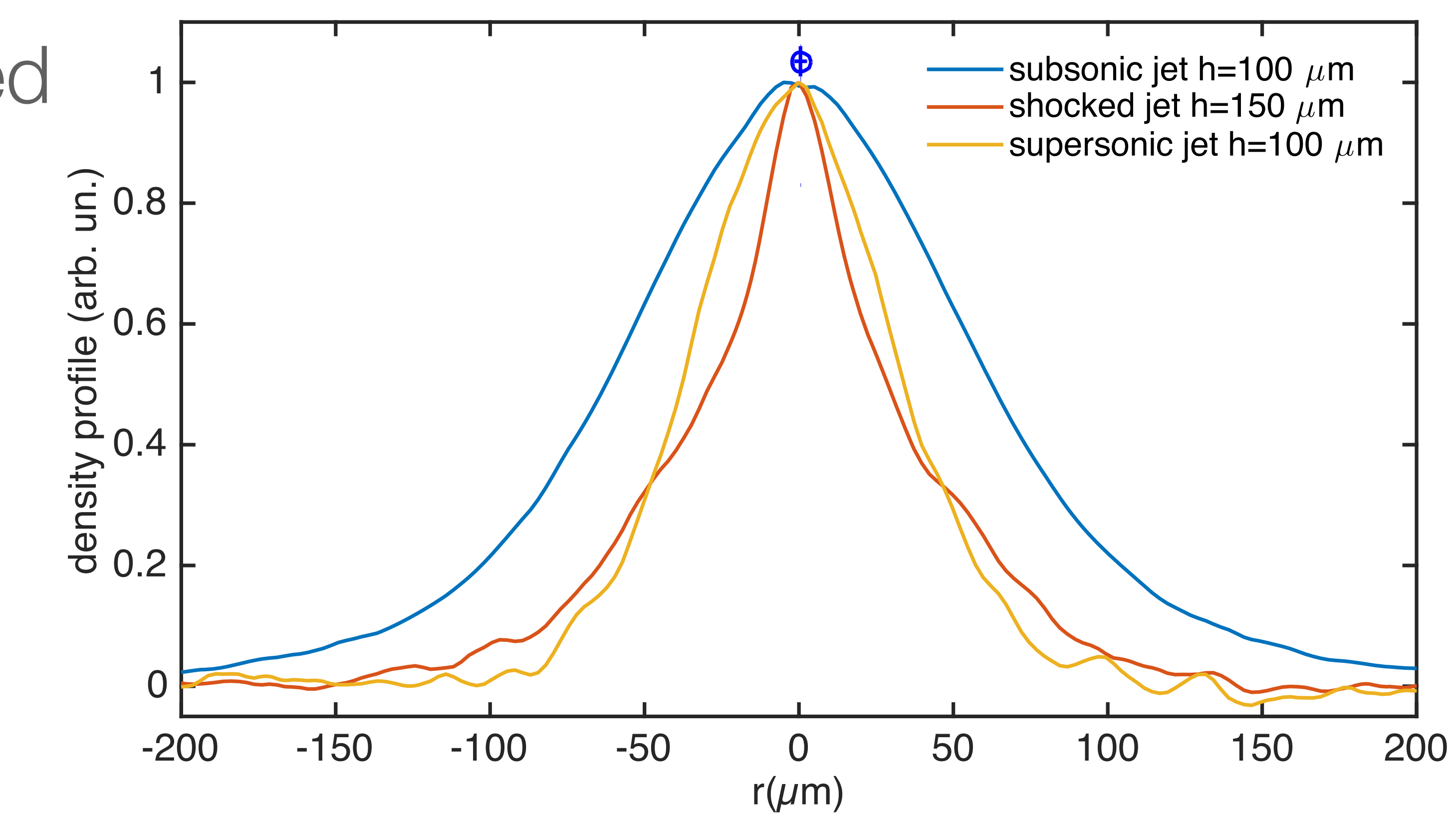


> R. D'Arcy et al. Phil. Trans. R. Soc. A (in press)

Published experiments with repetition rates up to 1kHz

- Laser wakefield acceleration experiments
- Laser systems with pulse energy of up to 10mJ and 1TW
- Hard focussing (f/3 or f/2) resulting in small sport sizes (few μm) and short Rayleigh length (few 10 μm)
- short targets with short density transitions compared to Rayleigh length required
  - Gas jet with various profiles used for experiments
  - operated in continuous flow
  - Adjusted pumping schemes required
- resulting beams:
  - up to 5MeV
  - charge up to tens of pC





> Z.-H. He et al. New Journ. of Phys 15 (2013) 053016
> J. Faure et al. Plasma Phys. Control. Fusion 61 (2019) 014012

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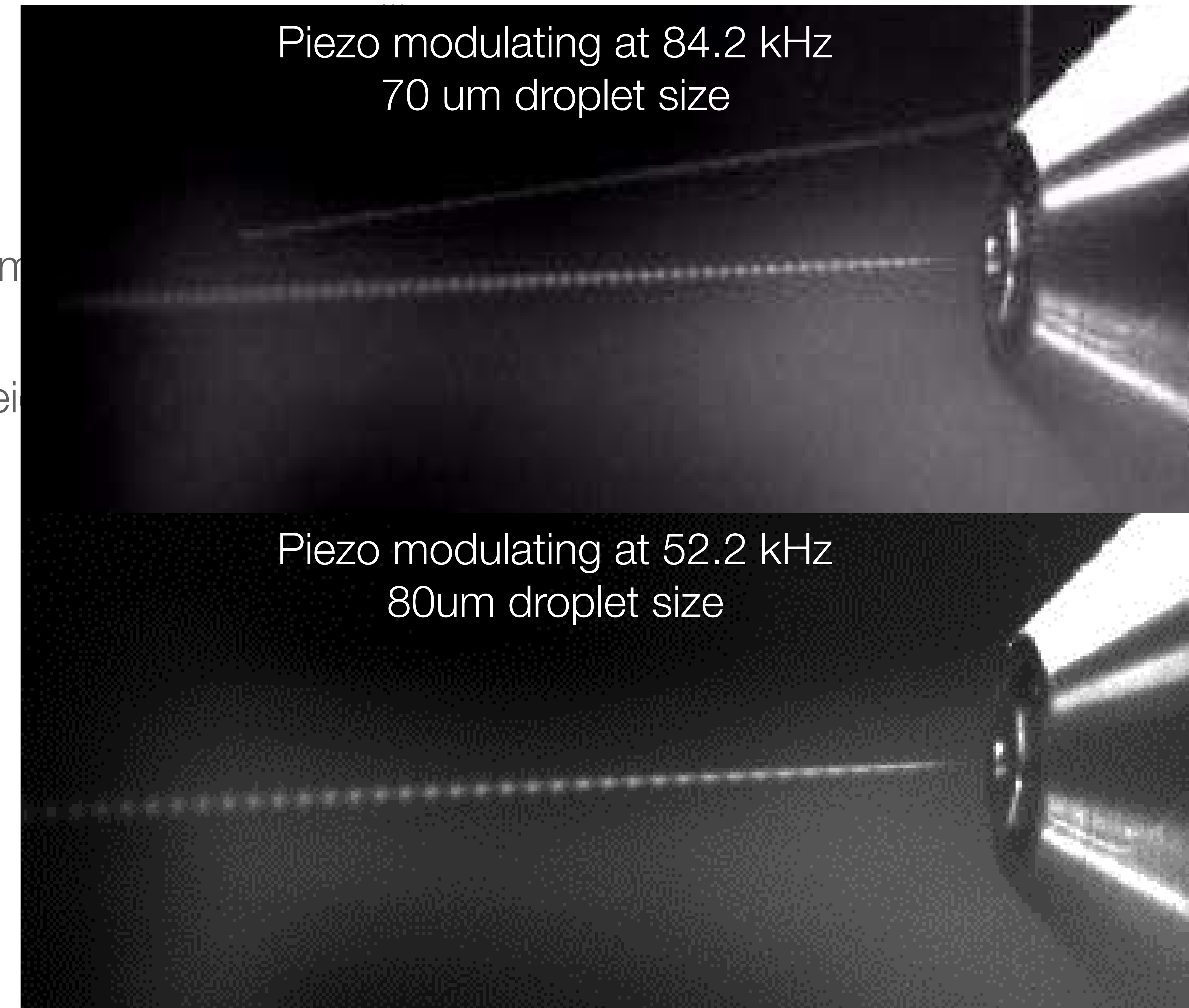


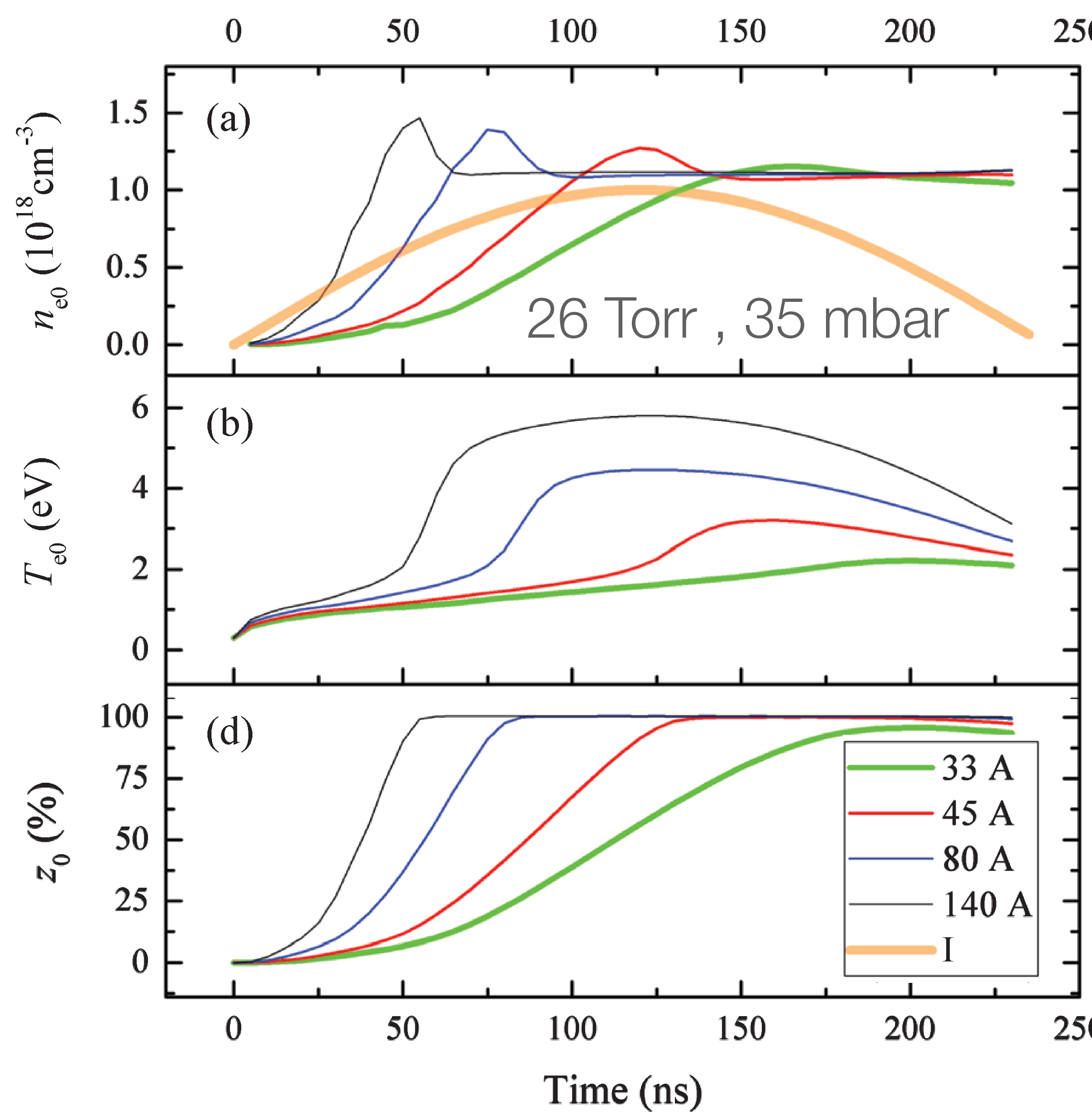
> curtesy of S. Goedde - measured at FLASH

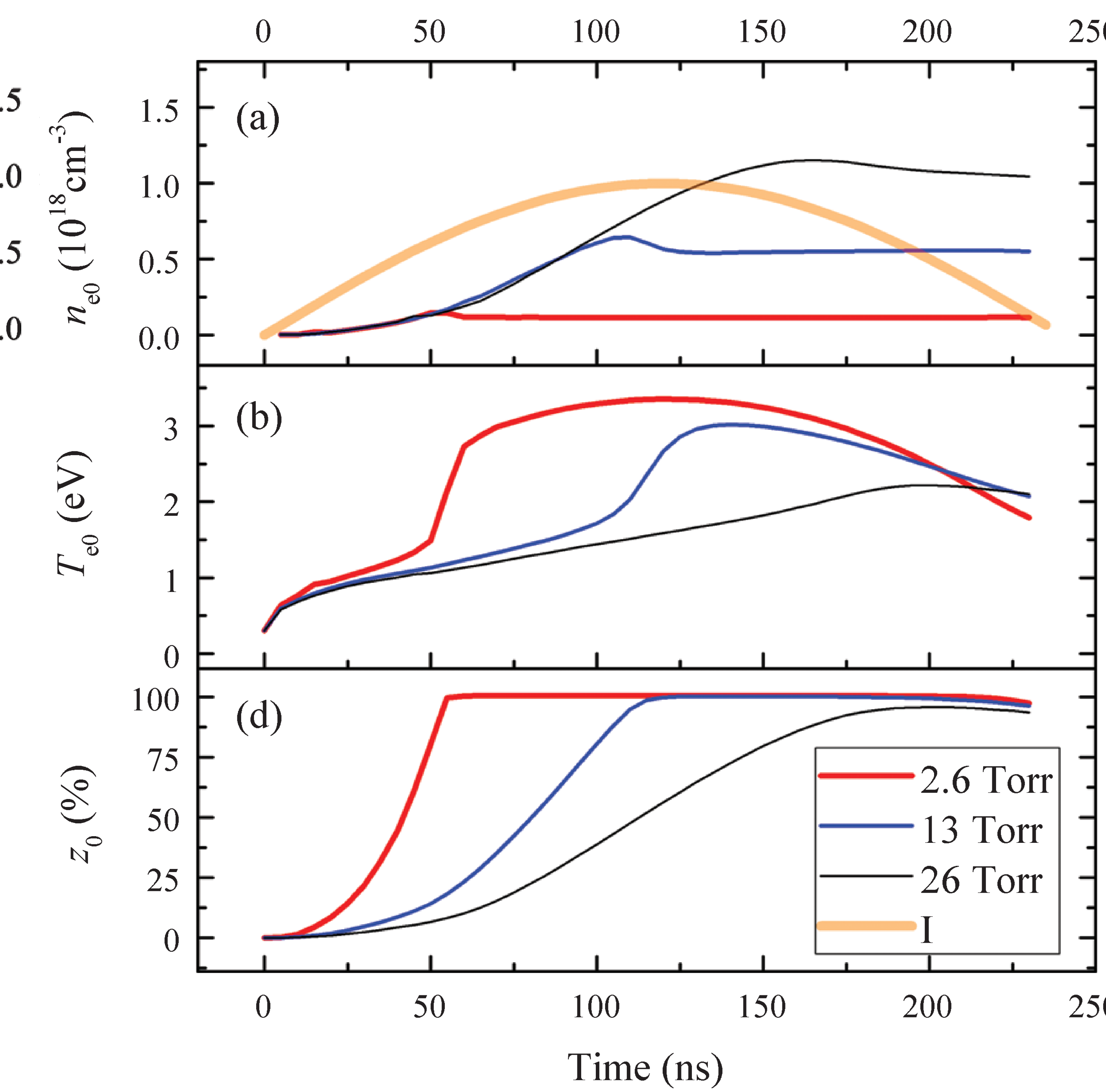
> Z.-H. He et al. New Journ. of Phys 15 (2013) 053016
> J. Faure et al. Plasma Phys. Control. Fusion 61 (2019) 014012

kHz plasma generation in discharge waveguides

- MHD simulations of a round 125 um capillary
- temperature increases after full ionisation
  - affecting ablation of capillary walls

- Electron temperature and density evolution dependence on current and pressure





- 1.5 kA/ mm^2 : Capillary not ablated
- 4.6 kA mm^2 and above : Single shot ablation of capillary walls observed

> Gonsalves et al. J. Appl. Phys. 119, 033302 (2016)

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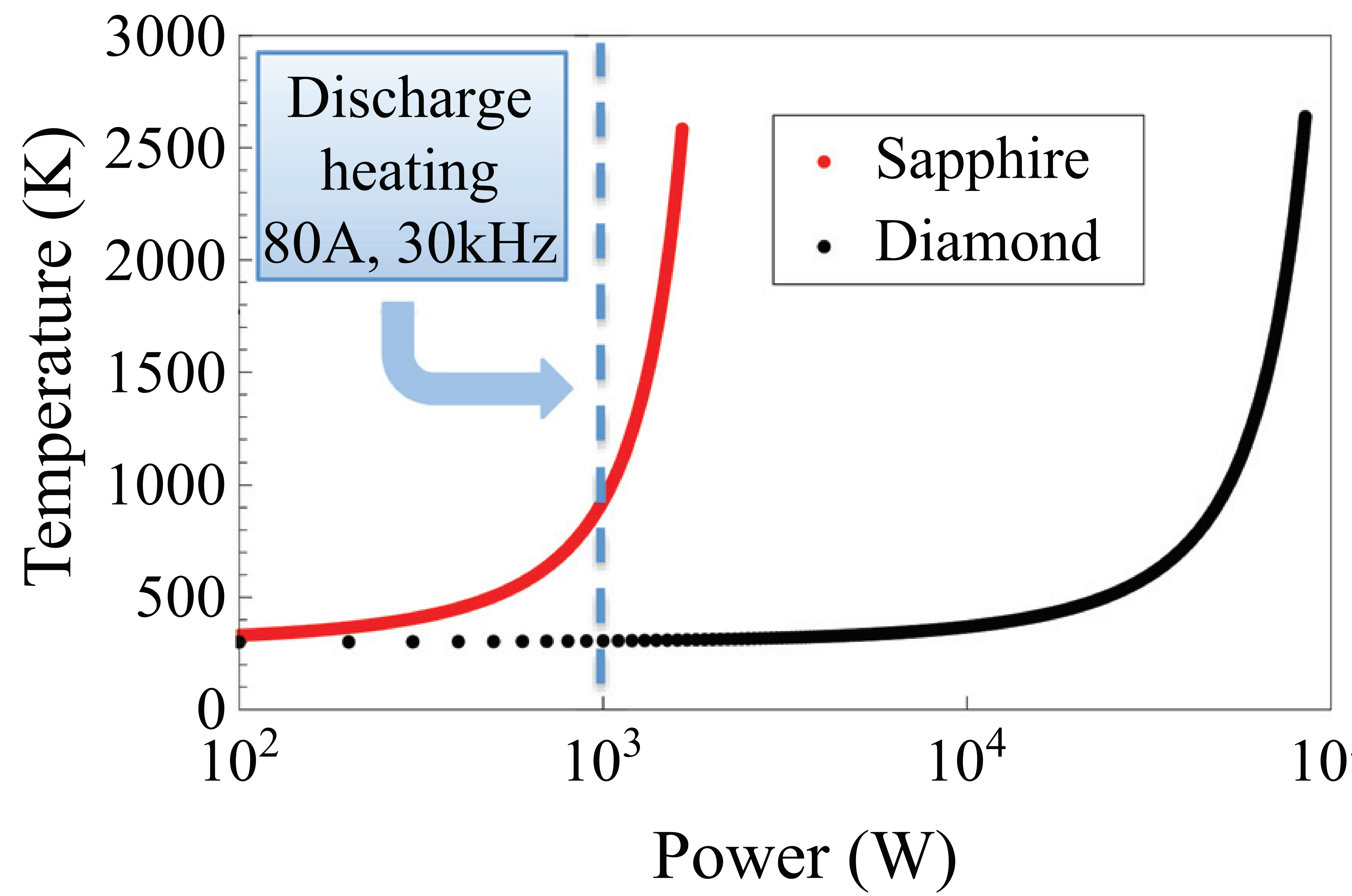
  - power deposition via spitzer resistivity, here: about 30mJ



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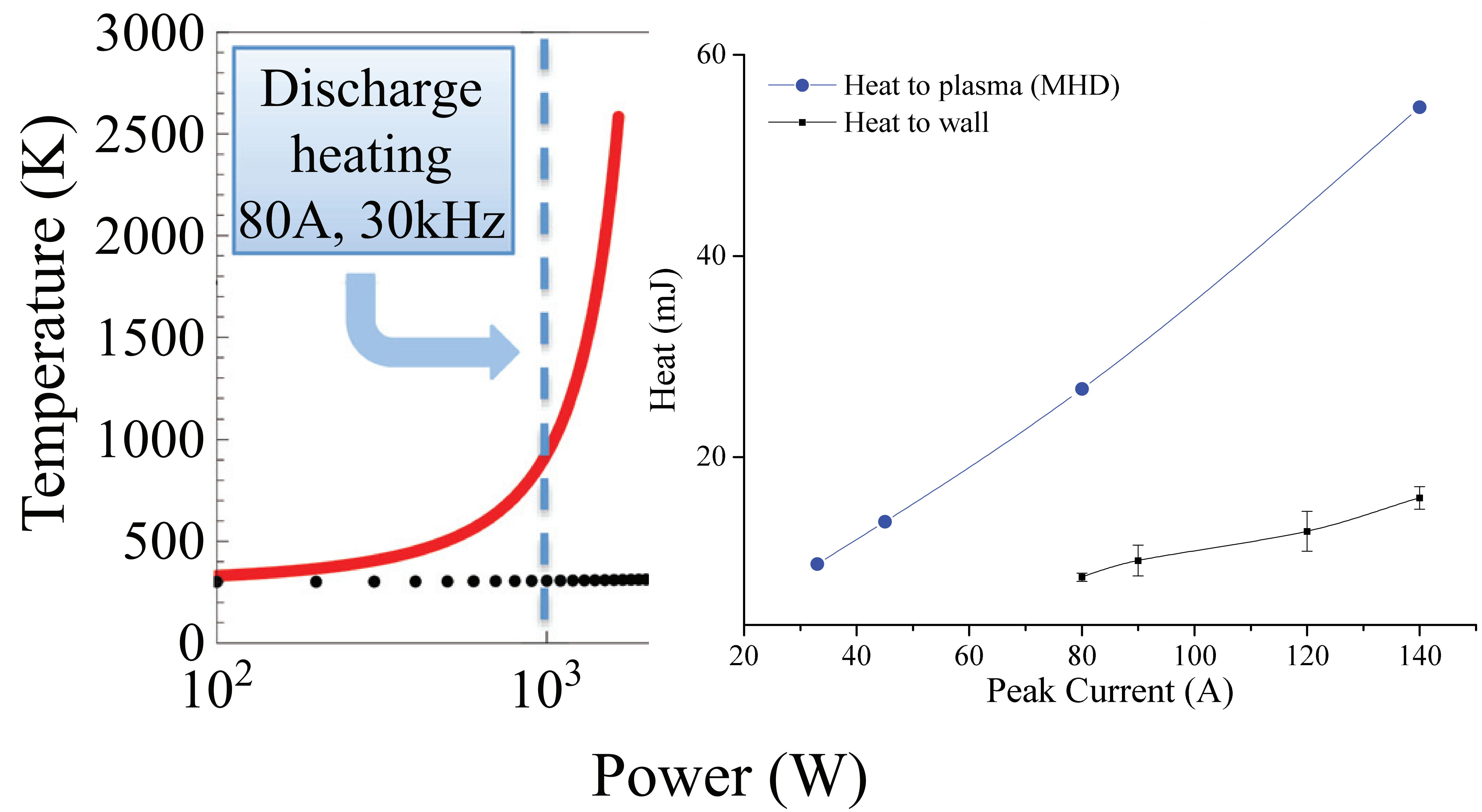

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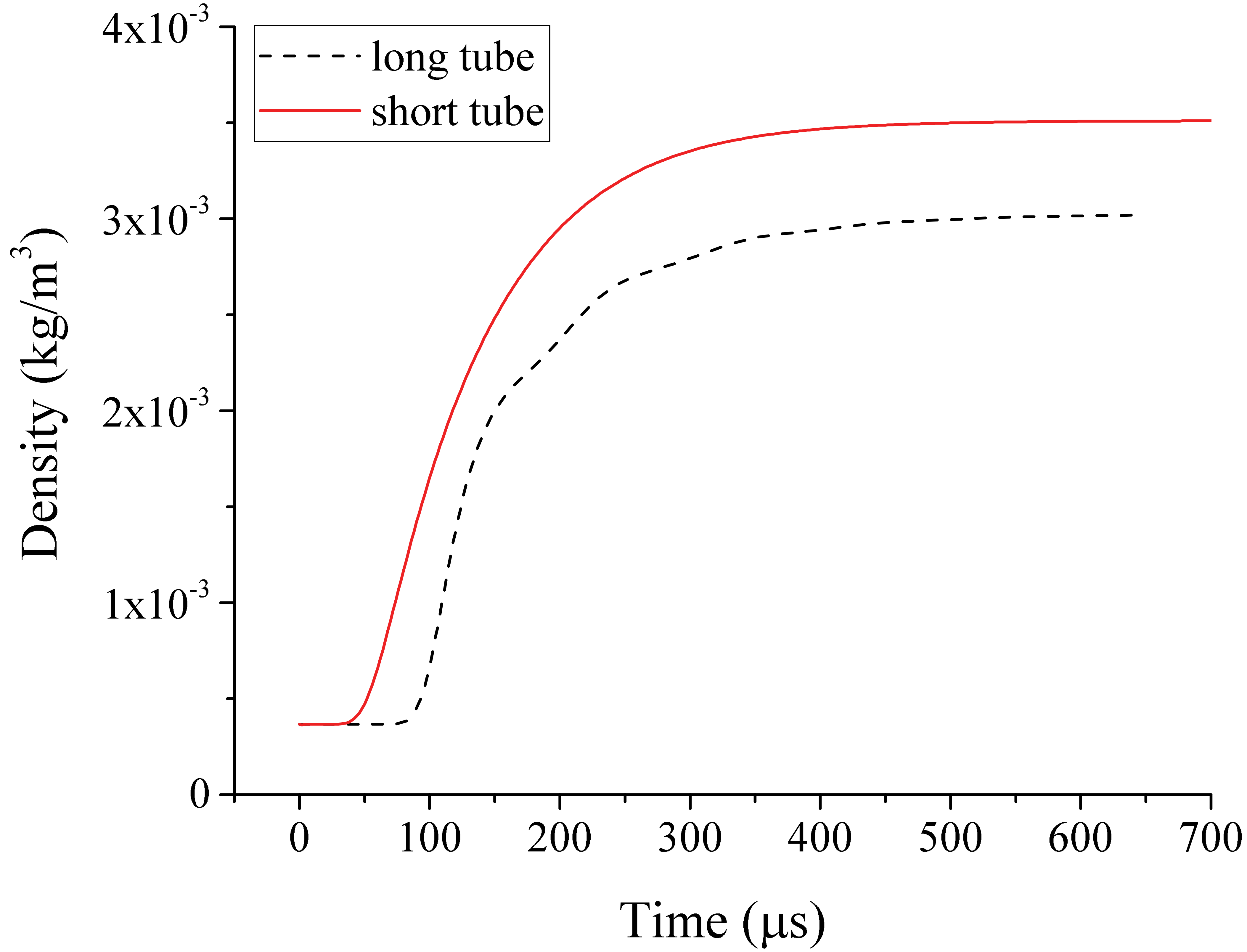
- Replenishing ejected gas
  - affected by configuration
  - few 100 us timescale



> Gonsalves et al. J. Appl. Phys. 119, 033302 (2016)

Experiments now vs experiments in future

[1] W.S. Cooper III and W.B. Kunkel; Phys. Rev. 138, 4A (1965), 1022

Currently: Start from scratch

- Gas exchanged before arrival of next shot
  - In kHz experiments with gas jets as well as in gas cells
- In vapour ovens: up to 10 Hz operation in closed volume
  - Plasma completely recombined and gas has homogenised
  - However beam energy deposition has been observed already at FACET

What lifetimes can be expected for plasmas?

- electron-ion recombination times in hydrogen plasmas: 100us timescale[1]
- excited species lifetimes: 2s state ~120 ms
- after recombination: rotational and vibrational state distribution?

Increasing repetition rate: Plasma reexcitation

- Build up time to the state desired for operation
  - how long does it take to get to equilibrium
  - influence on plasma density profiles
  - how long do beam induced plasma perturbations exist?

Plasma evolution: Density perturbation timescales

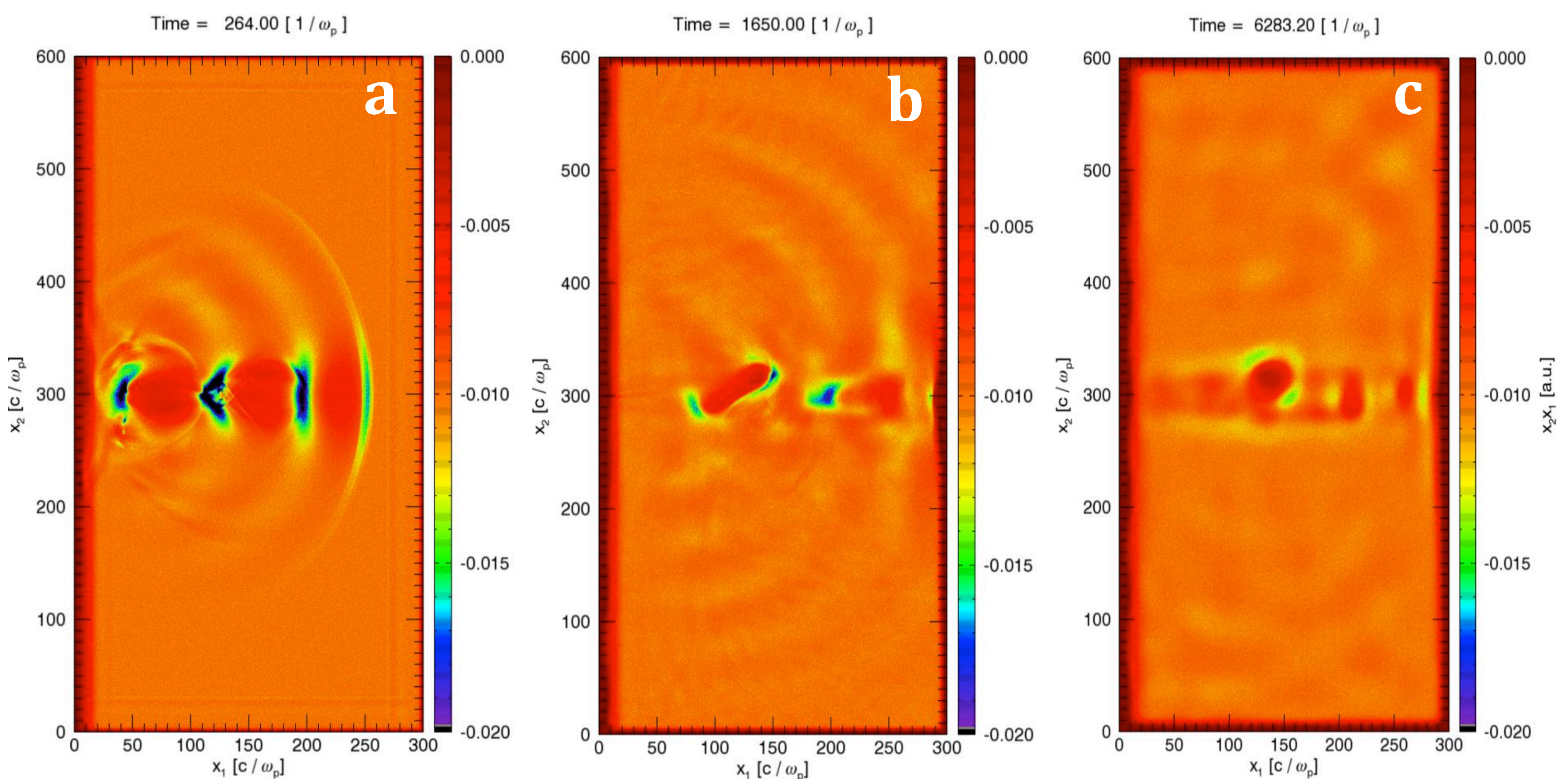


Figure 1: Laser wakefield LTE snapshots of **plasma electron density in real space** at times, t = **(a)** $264\frac{1}{\omega_{pe}}$ **(b)** $1650\frac{1}{\omega_{pe}}$ **(c)** $6283.20\frac{1}{\omega_{pe}}$.

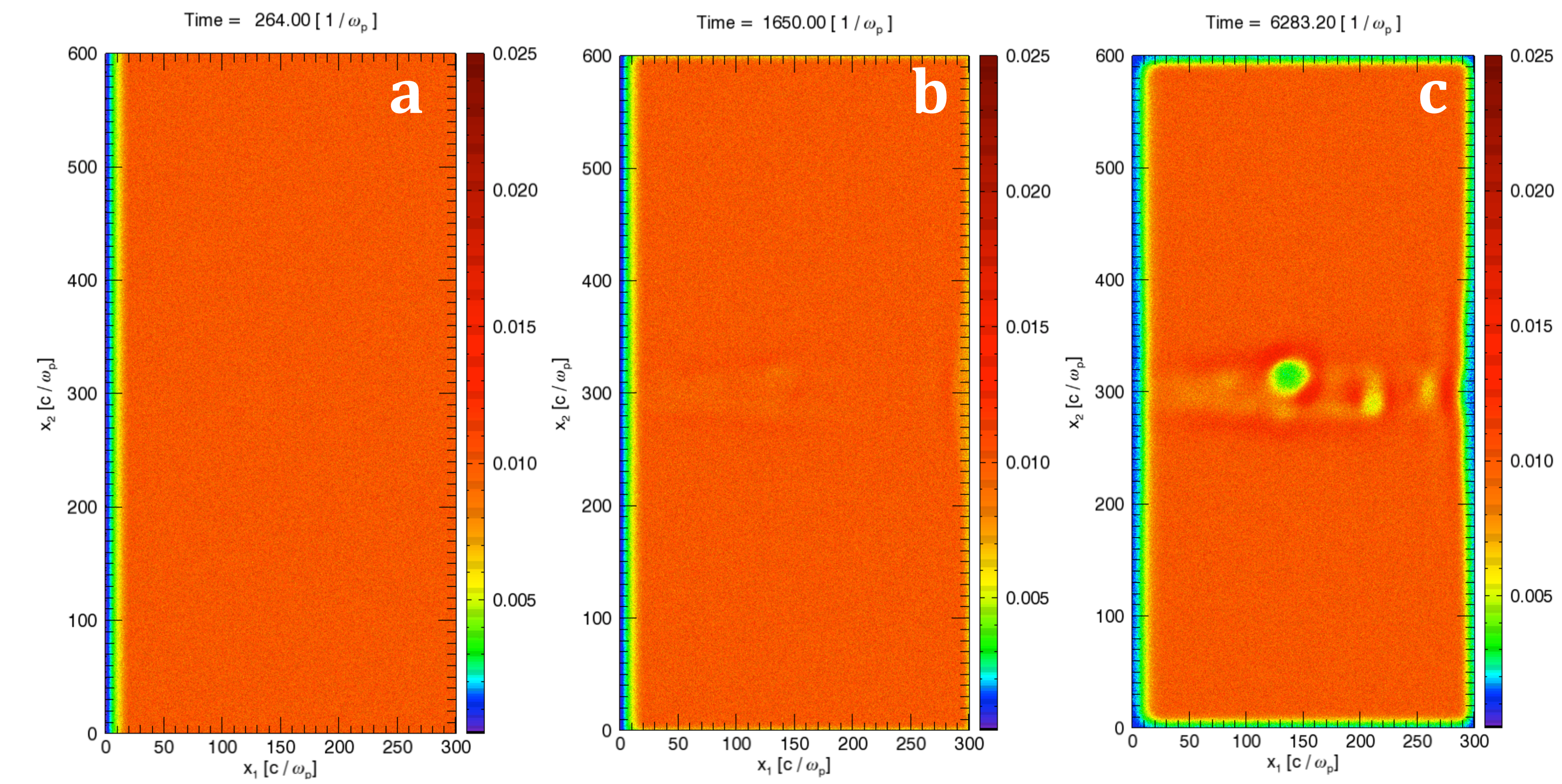
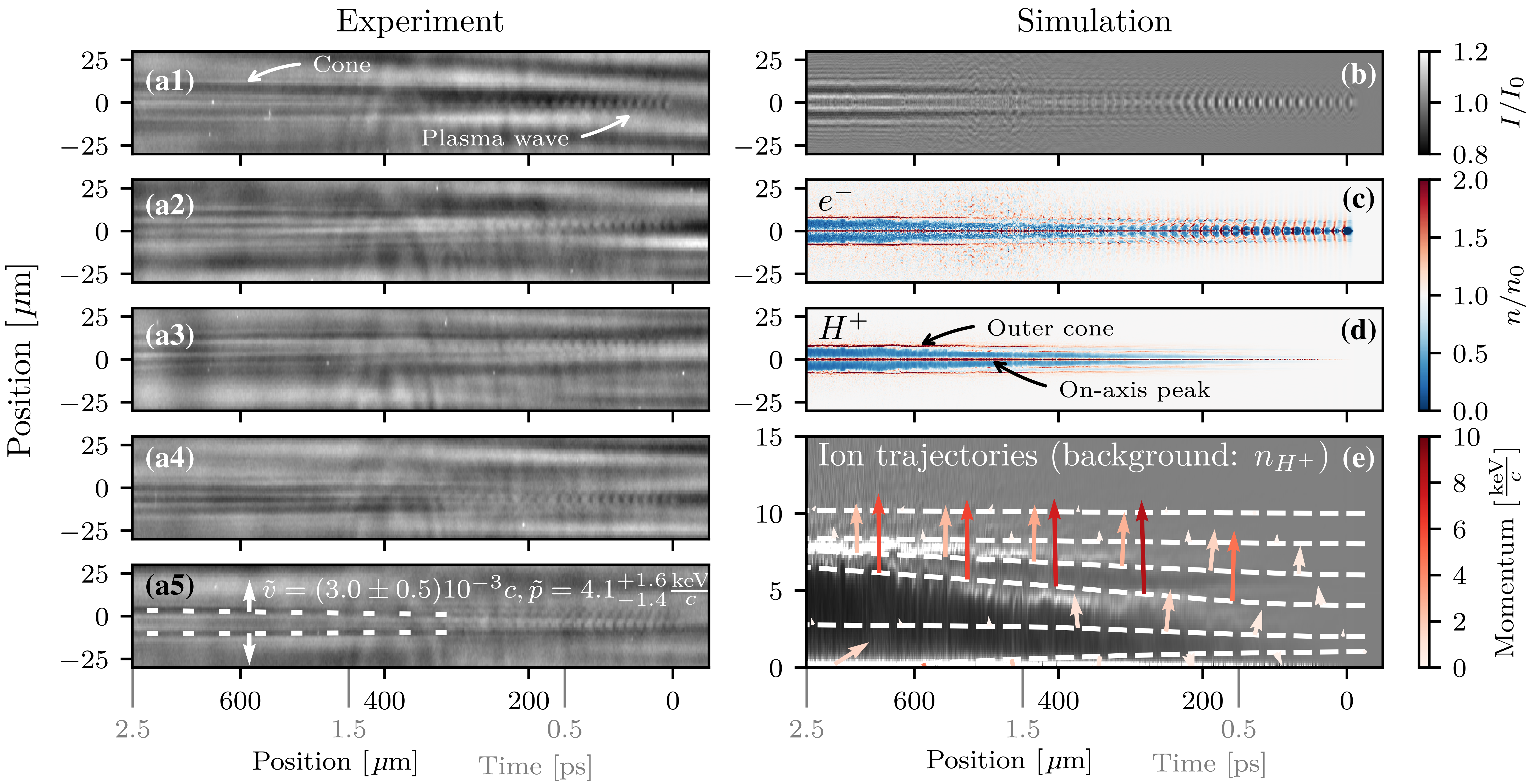


Figure 2: LTE snapshots of **plasma ion density in real space** at times, t = **(a)** $264\frac{1}{\omega_{pe}}$ **(b)** $1650\frac{1}{\omega_{pe}}$ **(c)** $6283.20\frac{1}{\omega_{pe}}$. We can observe onset of ion motion in **(b)**.

- $1/\omega_{pe}$ ~ 20 fs -> Distortions of plasma electron density still visible after 120 ps
  - ion density distortions start to show up at about 120 ps
- recent experimental results: ion column effects for multiple picoseconds

> A.A. Sakai et al: MOPAC 10 LONG TERM EVOLUTION OF PLASMA WAKEFIELDS
> M.F. Gilljohann et al. PHYSICAL REVIEW X 9, 011046 (2019)

Plasma evolution: Density perturbation timescales



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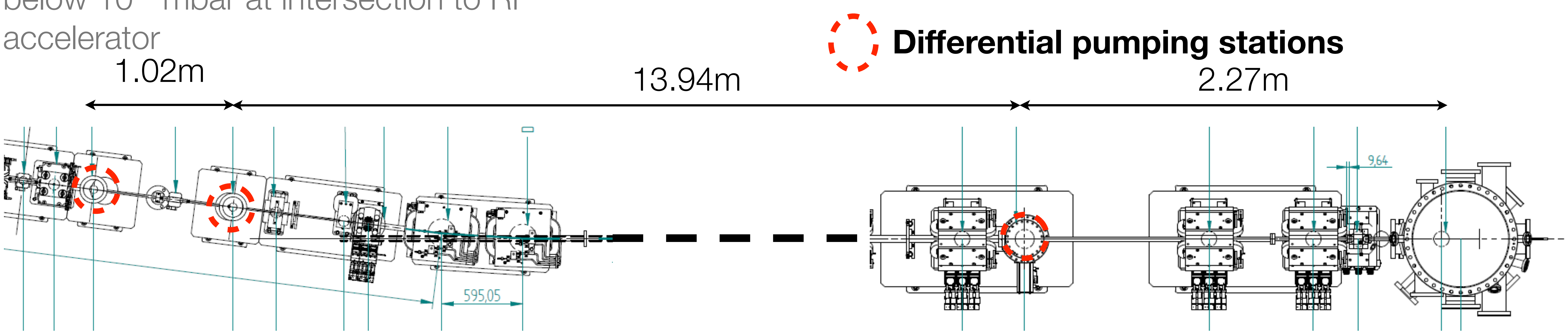
What are the problems involved

Physics		Engineering
	target	- gas removal - lifetime
- ionisation - equilibrium - perturbations	*background plasma*	- repetition rate
- energy deposition of drive beam - alternate ways of energy extraction	*thermal load*	- efficient cooling
	efficiency	

Gas removal

- Differential pumping is well understood
- Efficient gas removal requires large pumping speeds, small orifice dimensions and ideally bent section
- Compact integration available, see A. Maier Wednesday 9:00
- Requirement for FLASHForward: pressure below 10^{-8} mbar at intersection to RF accelerator

- Pumping speeds required for 20 mbar l/s H2 operation
  Experimental chamber: Removing 95% of the gas load
  2 x 2000 l/s turbo pump
  First stage: Removing 4.95% of the initial gas load
  700 l/s turbo pump
  Second stage:
  700 l/s turbo pump
  Third stage:
  700 l/s turbo backed by 80l/s turbo

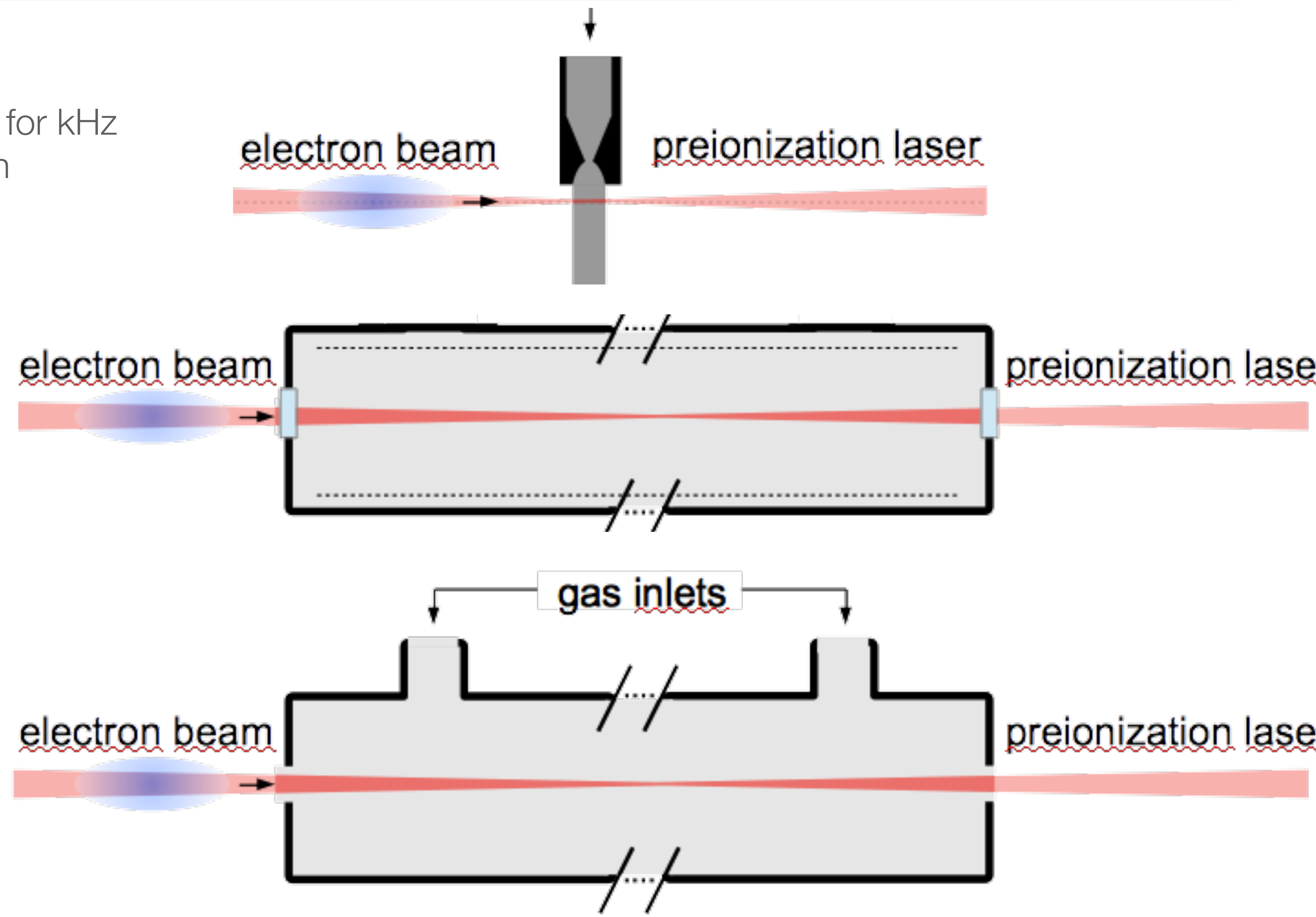


Currently existing gas target concepts

Gas Jets:
- pulsed operation (~ms) -> DC gas flow for kHz
- poor scaling for multiple cm to m length

(Metal) Vapour Ovens:
- density controlled thermally
- proven homogeneity on meter scale
- operation (usually) with windows

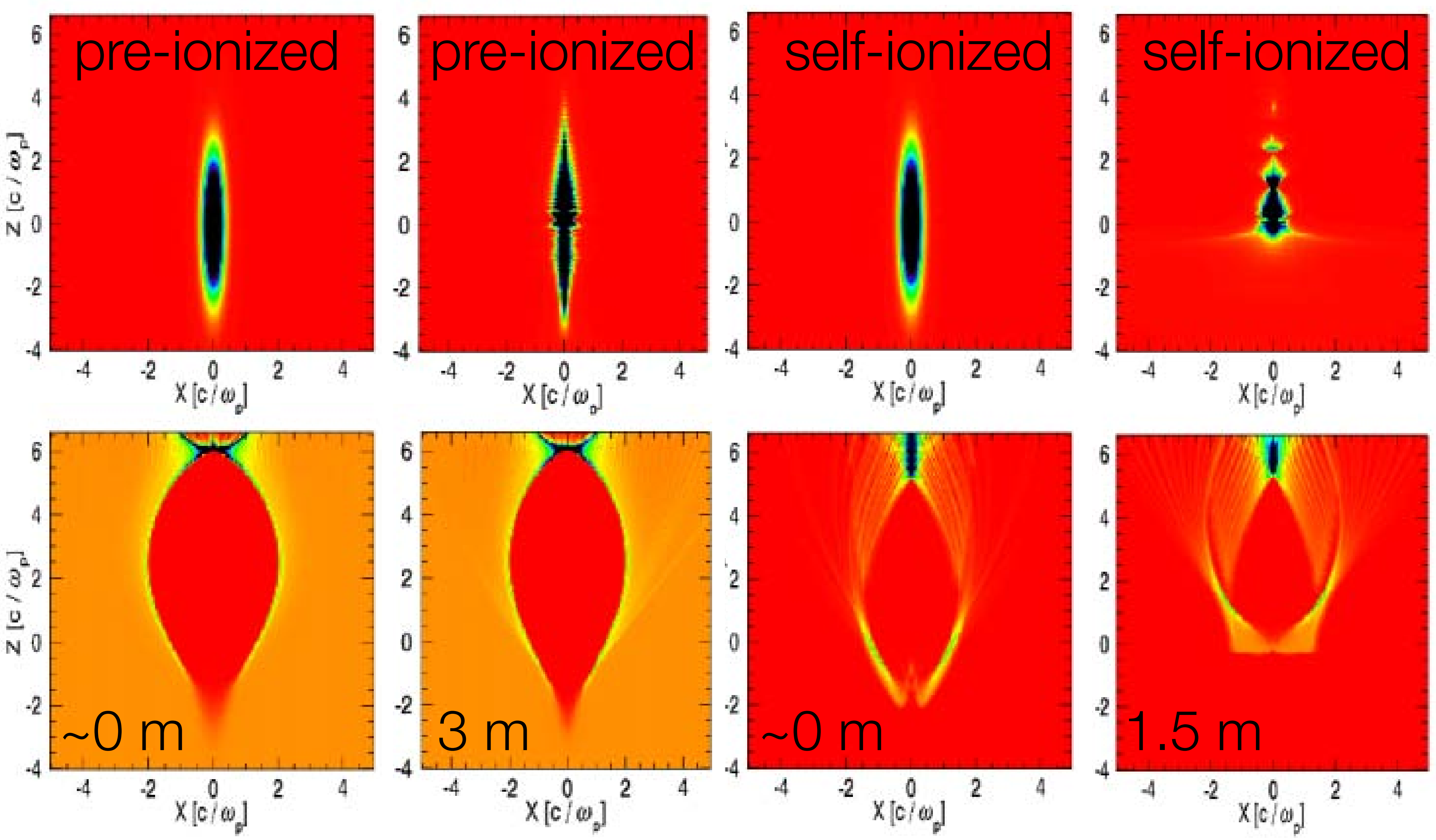
Gas Cells:
- filling time requires CW gas operation
- homogenous gas density distribution
- various ionisation schemes
- no windows required



Plasma generation

Ionisation by beam

- Sufficient field strength of intended drive beam required
- Electron beam driver: Head erosion
- Complex ionisation dynamics on few femtosecond scale



> M. Zhou et al. Proc. PAC07 No. 3064 (2007)

- Concepts for mitigation have been demonstrated
  - non matched beam with larger beta function
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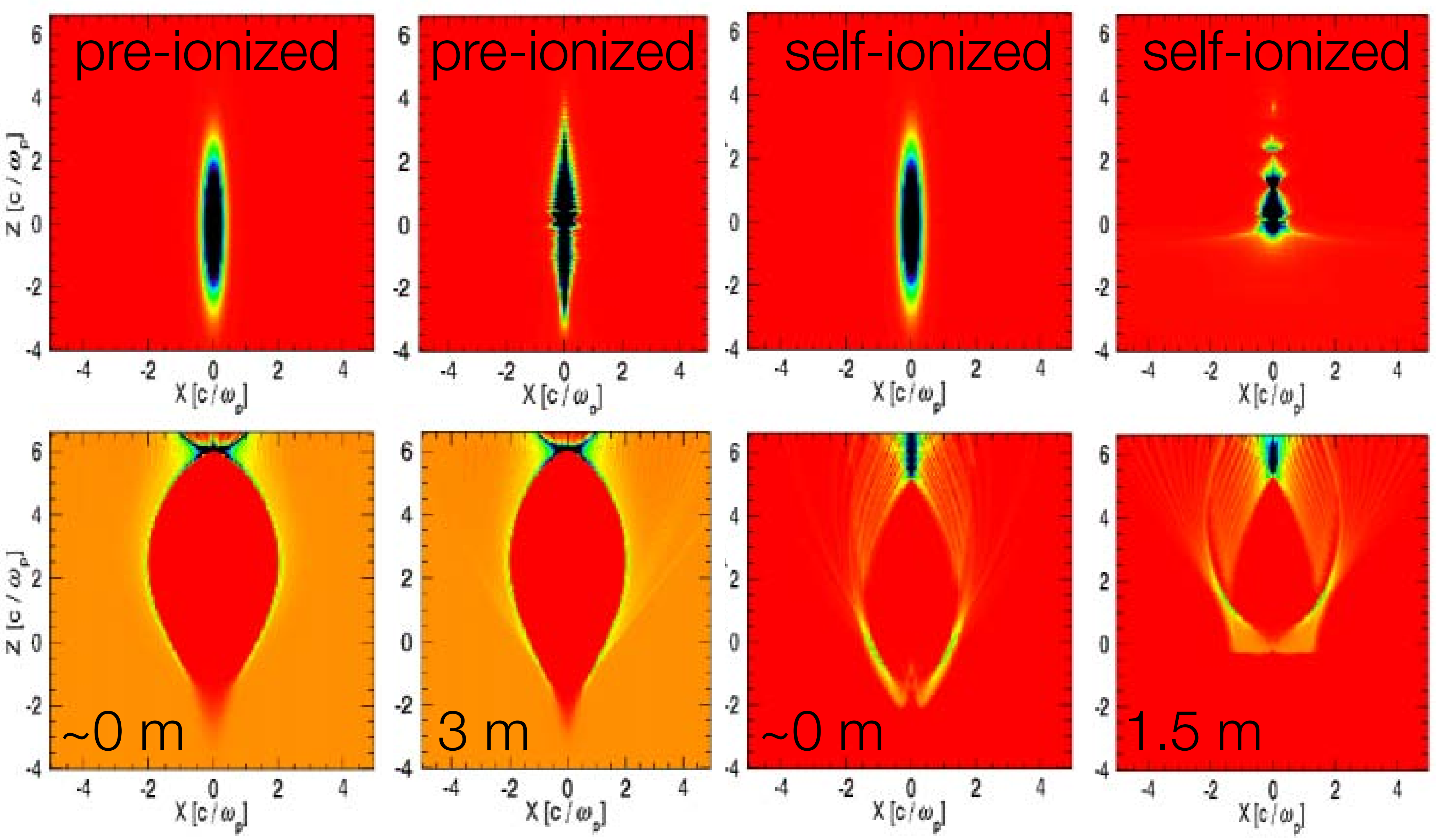

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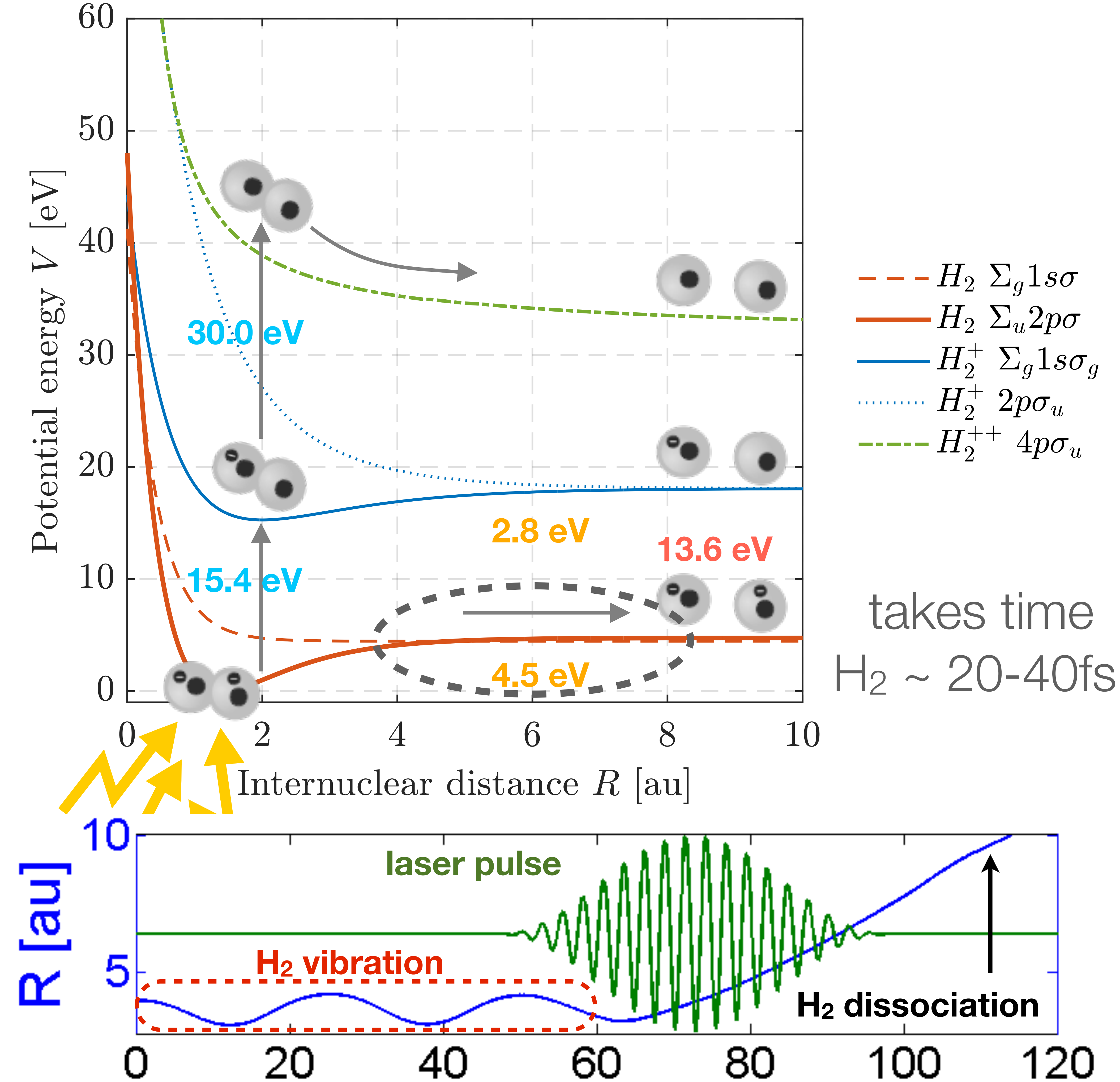

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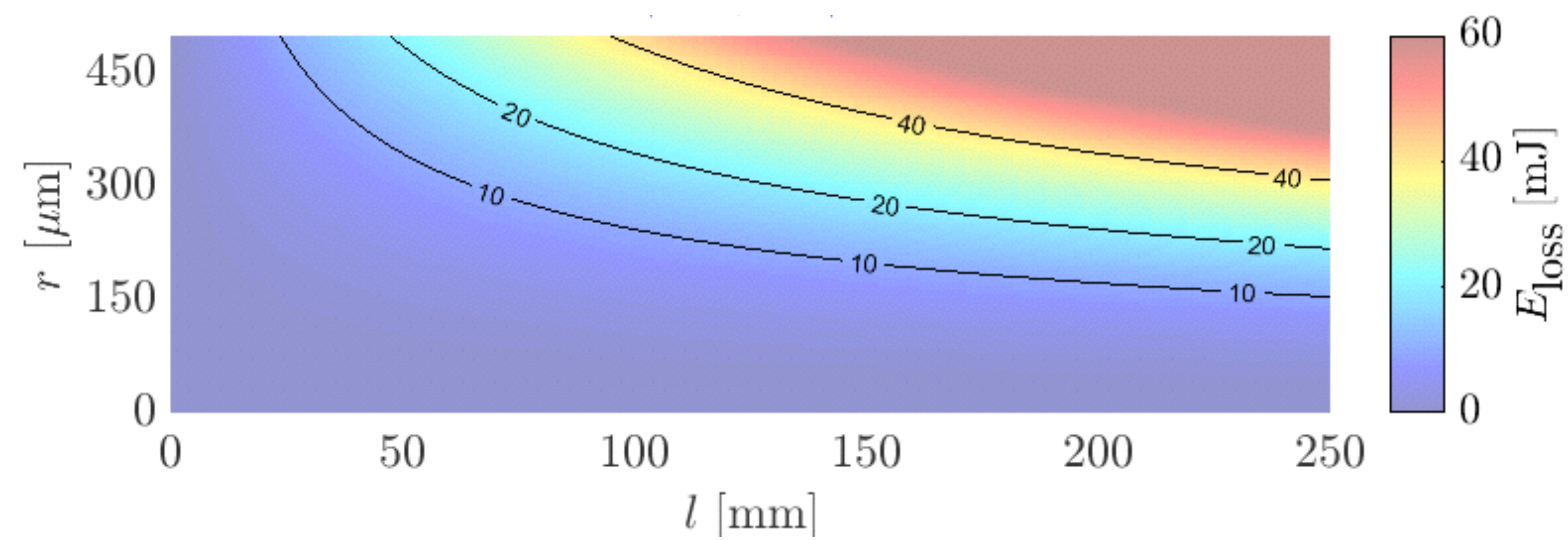
Ionisation by additional beam source:

- Synchronisation, drifts, stability (see A. Maier Wednesday 9:00)
- Plasma channel length and diameter -> weak focussing
- Points to tackle: Repetition rate and average power

Laser beam energy loss for plasma generation using H atoms electron density: $2x10^{17} cm^{-3}$



- Experimentally observed at FLASHForward:
  - F# 360, ~300 mJ, ~50 fs: > 50 cm plasma channel at 10^{15} cm^{-3} level in Argon
- Experimentally observed at Awake
  - F# 360, ~450 mJ, ~100fs: ~ 10 m plasma channel at 7x 10^{14} cm^{-3} in Rubidium (lower ionisation energy!)

Ongoing laser development

- Not available, however demand for kHz rep rate, few tens of femtosecond Joule class laser systems exists, e.g. kBELLA / KALDERA
- multiple avenues are currently being investigated :
  - Ti:sapphire
    - *Incoherently combined fiber lasers*
    - *Pumped by diode pumped Yb:YAG laser*
    - *Thin disk laser*
  - Tm:YLF Diode pumped, gas cooled
  - Fiber lasers:
    - *Coherent pulse stacking, coherent beam combining, spectral combining*
    - *Multi-core fiber laser with coherent beam combining*
- Timescale for development ~10 years
  - See recent report on Laser Technology of k-Bella and Beyond!

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High voltage discharge generation

- Various concepts of energy storage and release
  MOSFET switches offer great potential
- Power deposition within target

- Importance also for other potential topics, e.g. APLs (see presentation by Carl Lindstrøm Thursday 13:30)
- Pulse shape depends on configuration
- For impedance matched network: almost square wave voltage pulses
- Desired: independent tuning of current amplitude and pulse duration
- Extending plasma length is tricky
- Average and peak current capabilities of solid state switches (MOSFETs) are increasing
- Push-Pull configurations possible
  - FLASHForward setup:
    2 thyratron switched PFNs with 1.6kA peak current and arbitrary inter-discharge delay

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High voltage discharge generation

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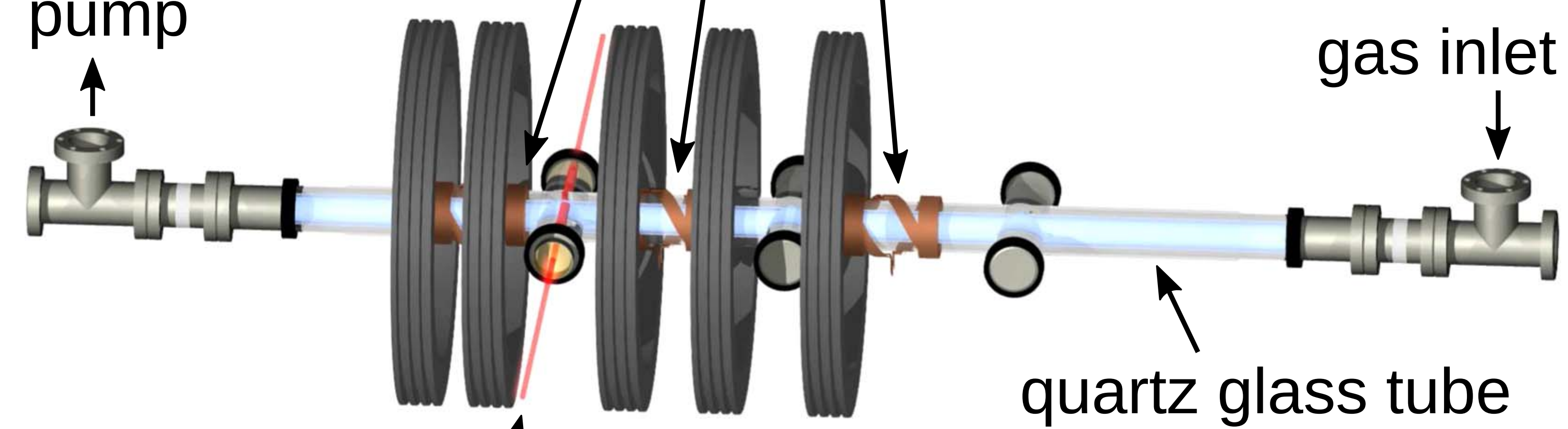
RF excited Helicon plasma

- Confinement of plasma electrons in a dense core



- plasma length > 1 m and diameters > 1 cm have been demonstrated
- observed electron densities ~ 10^{15} cm^{-3} at electron temperatures of few eV
- RF power in the tens of kW for plasma on meter scale
- typically operated pulsed at few 10 Hz, lower densities in DC
- Theoretical investigations predict higher densities should be possible

- B. Butterschoen et al. Plasma Phys. Control. Fusion 60 (2018) 075005
- I. Kotelnikov Physics of Plasmas 21, 122101 (2014)

Electron beam driver interaction with plasma

- Electron beam contributes to heating of the plasma
  - as seen at FACET: contributes to temperature increase in a vapour oven

- Assume efficiency of 40% and drive beam depletion:
  60% of the initial energy remains in interaction volume!

  - ultimately this energy will thermalise

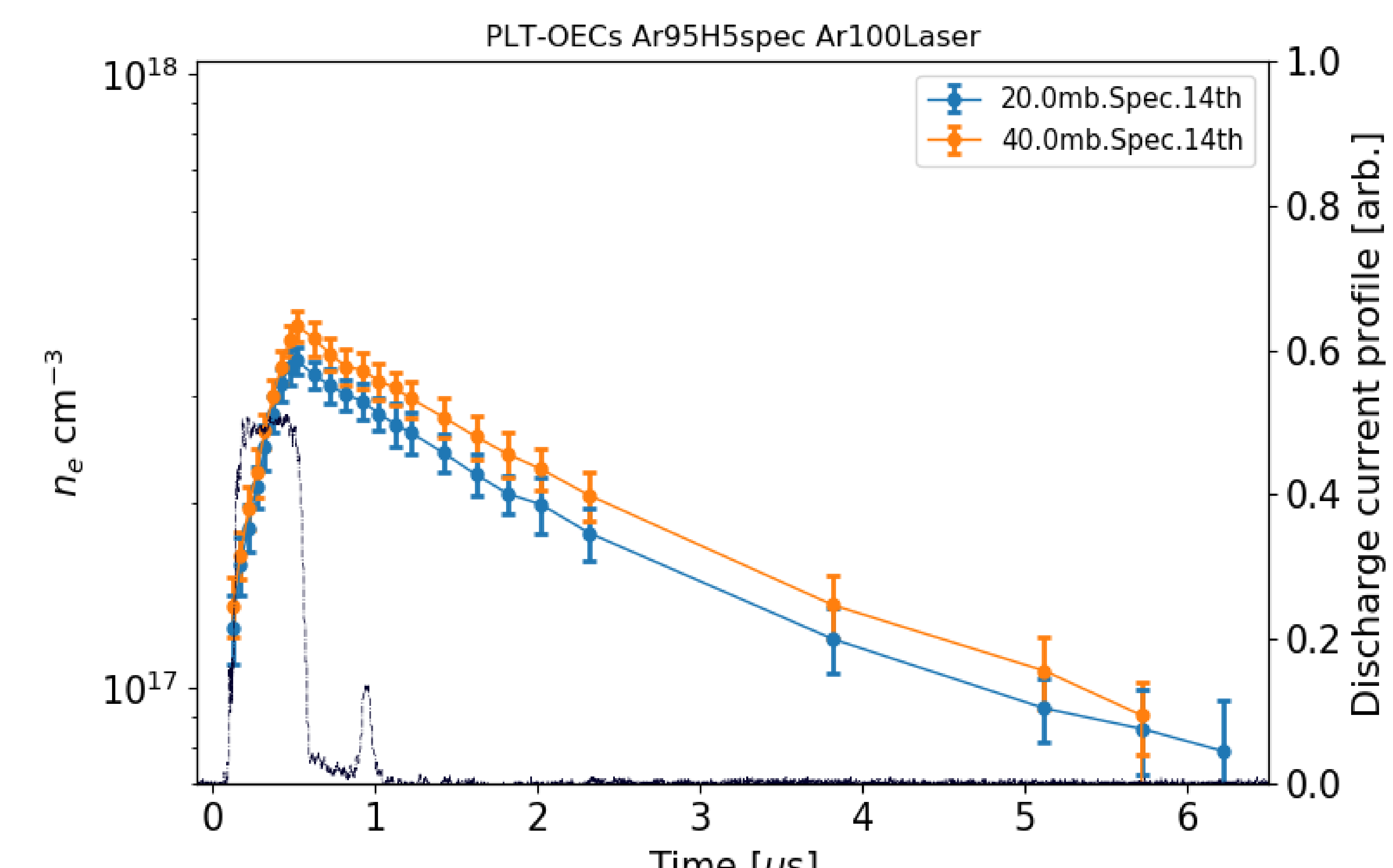
    - FLASH type drive beam ~1W per bunch, at 100 kHz this would translate to 60 kW
    - target length 40 cm: exceeding 1kW/cm

  - efficient cooling mechanisms required!

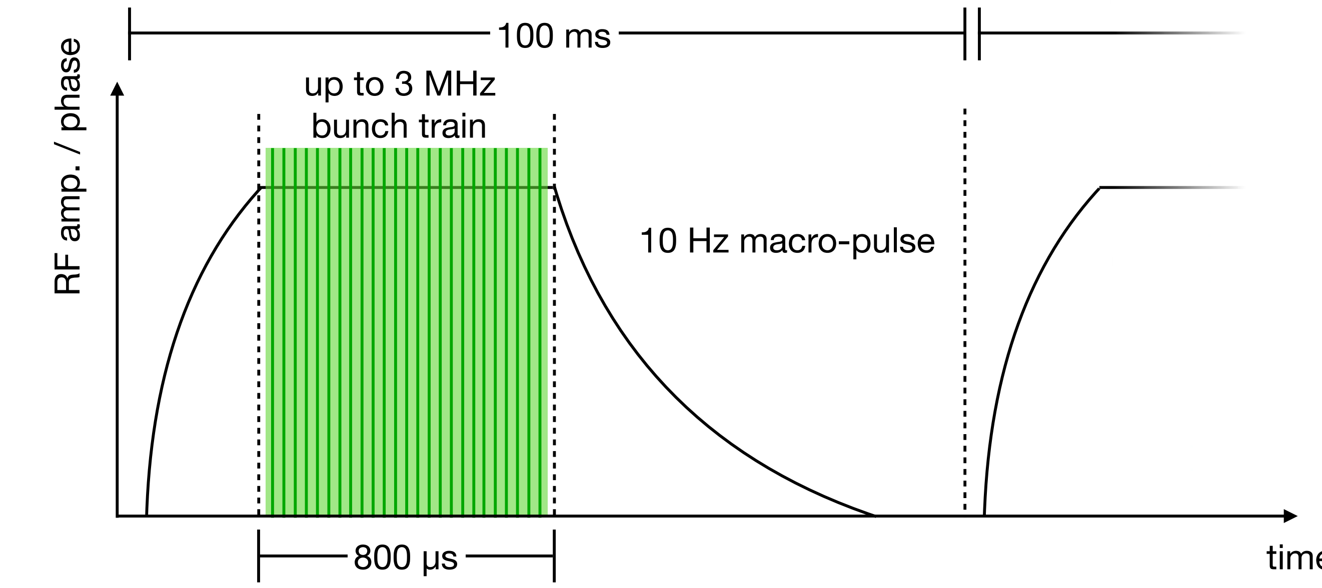
  - how much energy is dissipated via radiation processes?

  - recently explored: Additional energy extraction by active damping using a trailing laser beam
    - J. Cowley et al. PRL 119, 044802 (2017)

  - Alternative approach: Jump-start
    Use external source for first plasma generation, then the deposited beam energy to reexcite the plasma
    - a lot of influencing factors!



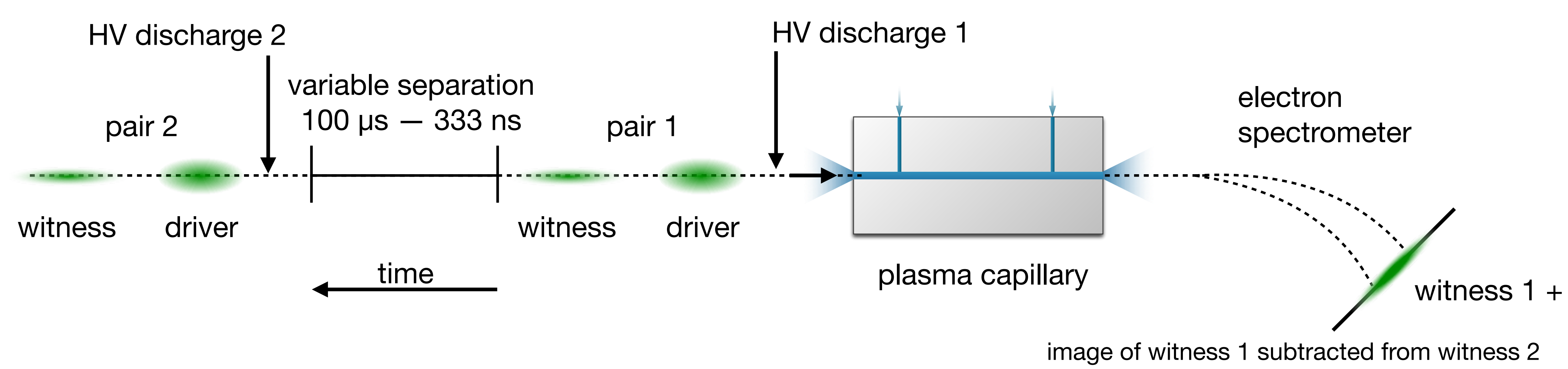
How can FLASHForward contribute



- Benefit of superconducting RF linac:
  - Adjustable operation rate in macro pulse from 3 MHz down to few kHz
  - Adjustable bunch charge from 1 nC down to few 10 pC

- Targets up to 45 cm length
- Plasma densities between 5 x 10^{17} cm^{-3} down to few 10^{14} cm^{-3}

- Exploration of plasma density perturbation timescales using the double discharge configuration



- Near future:
- Upgrade to a MOSFET switched discharge system for MHz-multi bunch operation
  - Existing expertise in development of current XFEL arbitrary bunch train kickers
- Investigate progression from unperturbed to equilibrium plasma formed by high repetition rate bunch train

See presentation Wednesday 14:10 on FLASH>> by Richard D'Arcy