Diagnostics for plasma ion and electron heat flow

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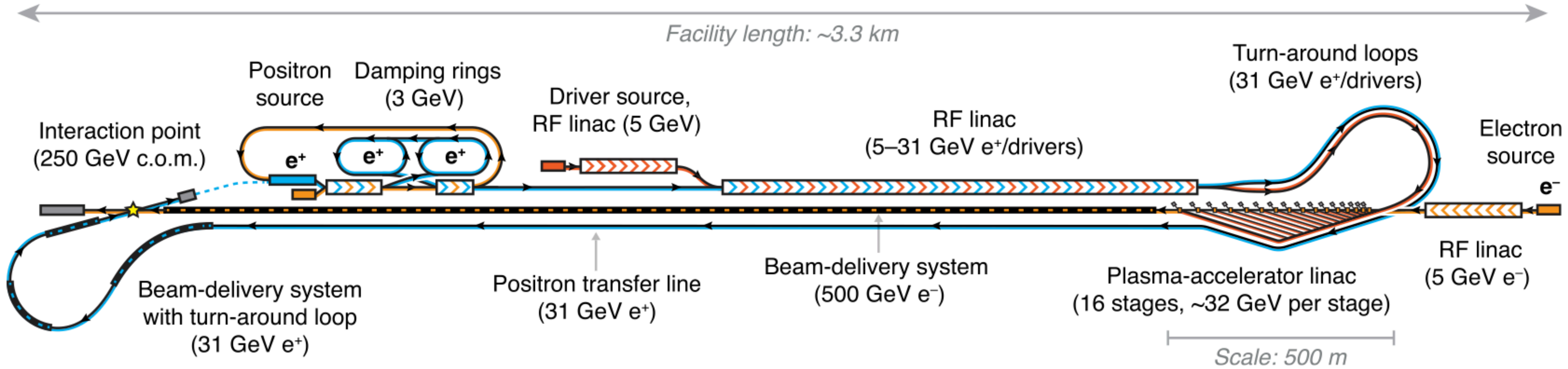
The importance of heating in wakefield accelerators

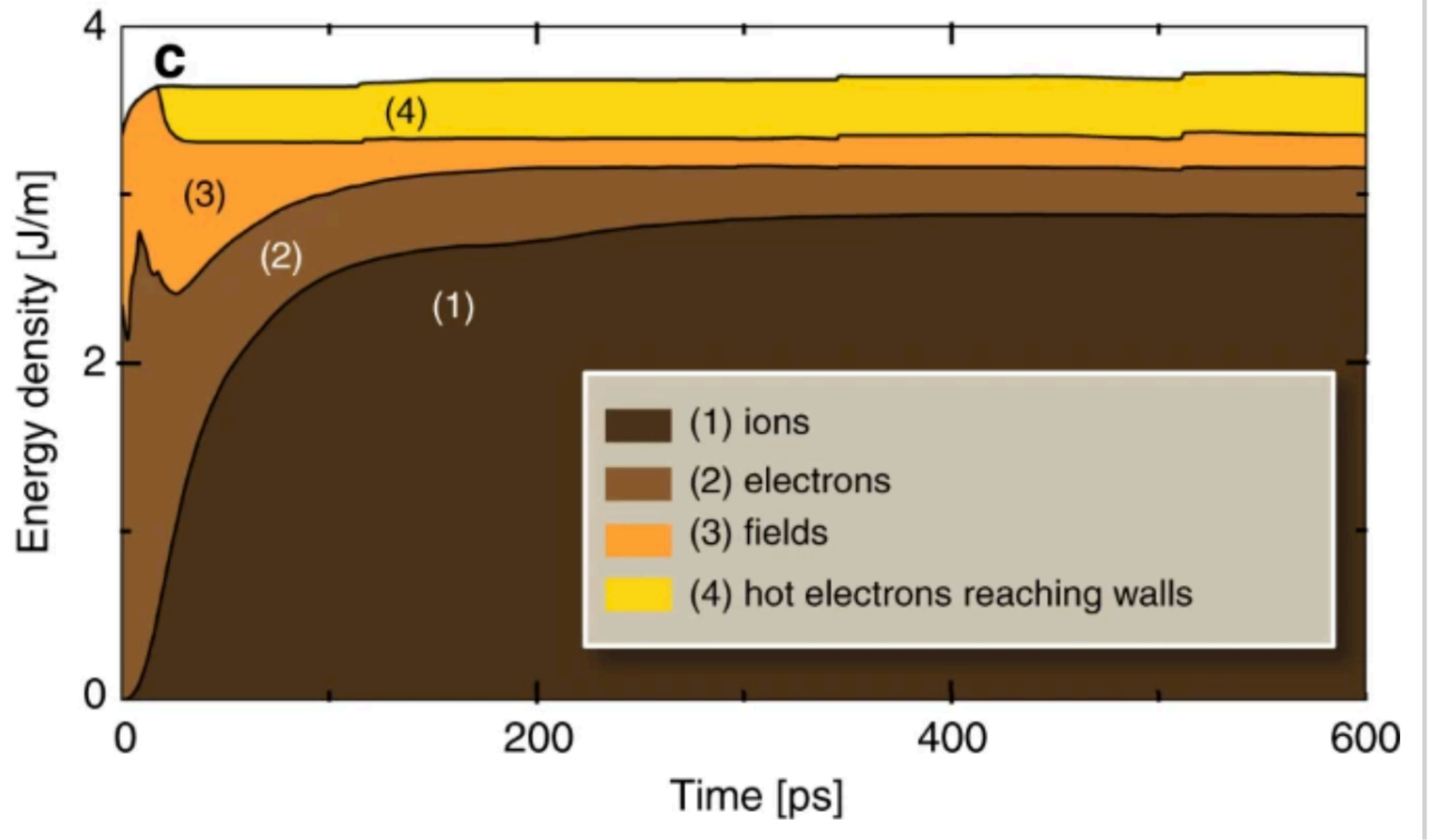
- **Plasma accelerators are in many ways close to being ready for applications**
  - Energy transfer efficiency > 40 %
  - Accelerating fields > GV/m
  - Beam quality maintained during acceleration
    - Energy spread, emittance, charge



- **But significant challenges remain**
  - Most applications require > thousands events/second to achieve required brilliance/luminosity
  - Putting all of the achievements above together creates new challenges
  - Target design and plasma need to cope with the average power deposited
    - Discharge
    - Energy deposited by driver
    - …

Heating and cooling mechanisms in PWFA

- **Gas is ionised by high-voltage discharge**
  - Ohmic heating of plasma from discharge current
- **Drive bunch/laser creates wake**
  - Witness/injected electron bunch removes energy
- **Hot plasma electrons transfer energy**
  - electrons > fields > ions > capillary
- **Timescales range from very short (femtosecond) to very long (millisecond)**
  - This creates significant difficulty in simulations of heat flow



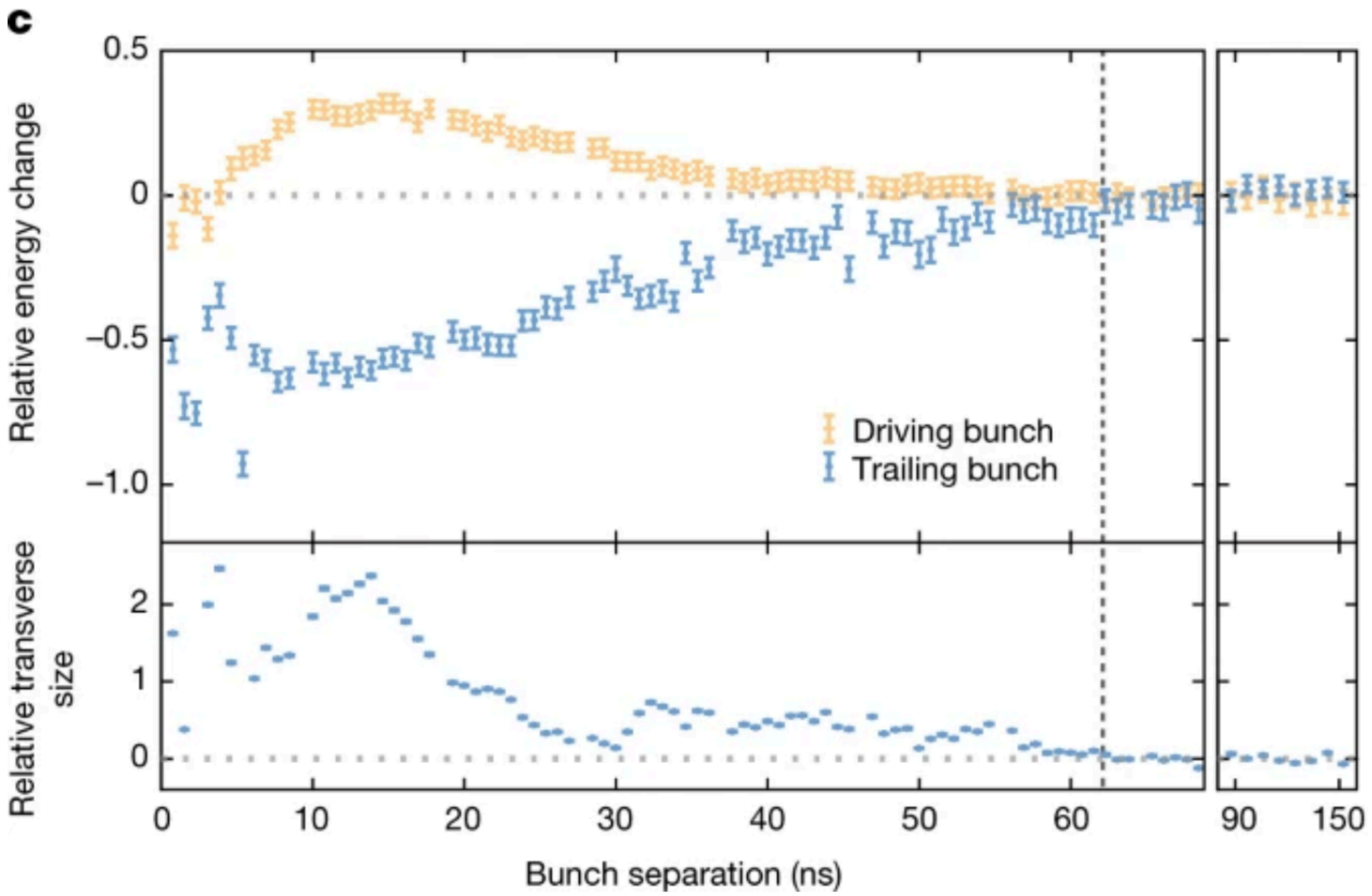
Zgadzaj, R., Silva, T., Khudyakov, V.K. *et al.*

Dissipation of electron-beam-driven plasma wakes. *Nat Commun* **11**, 4753 (2020).

We know that the plasma and target are heated but a quantitative start-to-finish understanding of heat flow is difficult to achieve - in simulations or experiments

What will limit repetition rate?

- **Experiments using witness bunch as a diagnostic have been performed**
  - ~10-100 ns minimum time between accelerating bunches
- **We already know that heating the plasma has implications for acceleration**
  - Shortening of plasma frequency
  - 'Smearing' of plasma density distributions
- **The plasma needs in a consistent state at the start of each acceleration process**
- **Beam based diagnostics could not differentiate between e.g. a change in density and and change in temperature**
- **This is a start but is far from showing the whole picture**
- **Other diagnostics are necessary to detangle competing effects…**



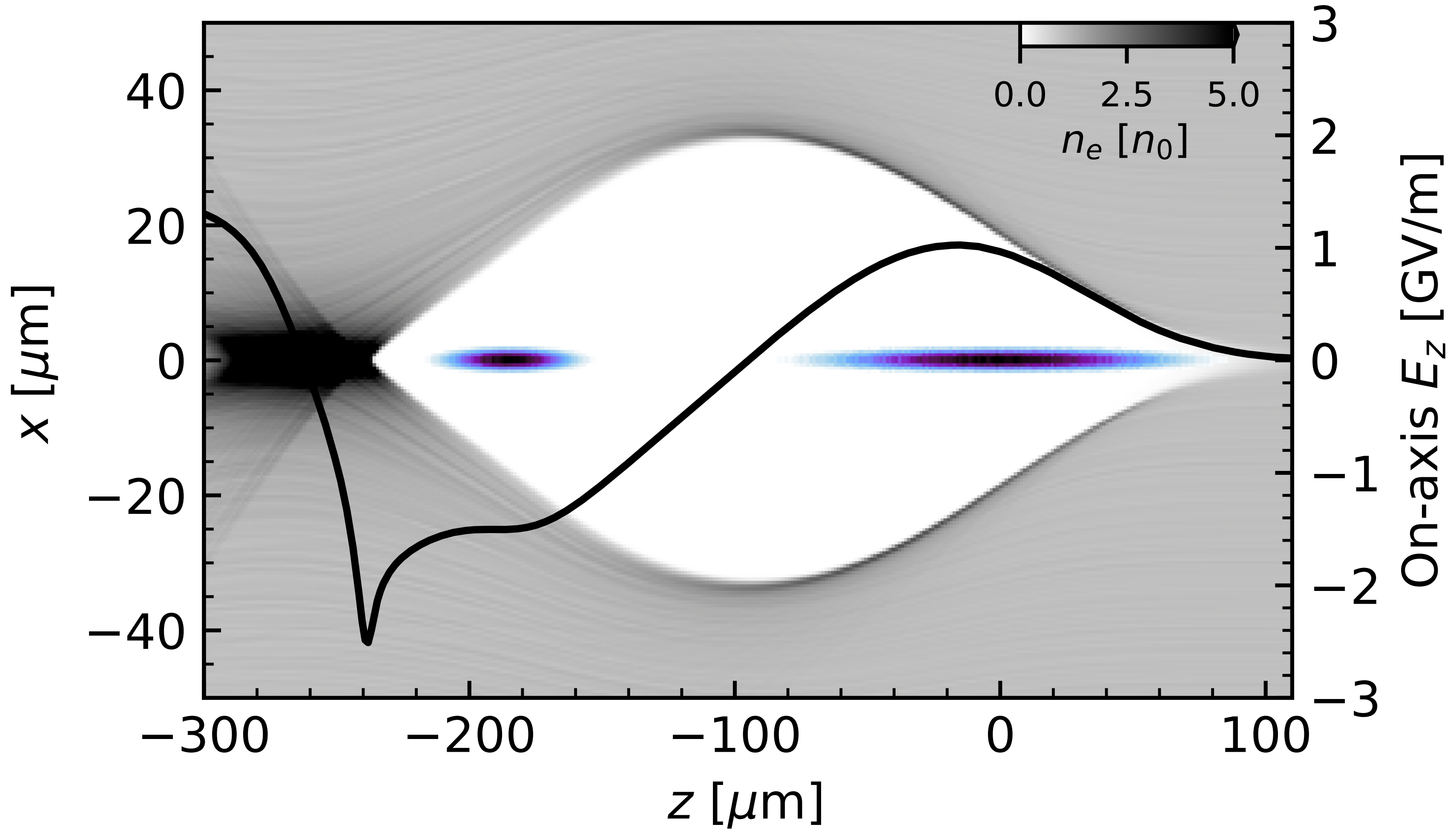
D'Arcy, R., Chappell, J., Beinortaite, J. *et al.*
Recovery time of a plasma-wakefield accelerator. *Nature* **603**, 58–62 (2022)

Pompili, R., Anania, M.P., Biagioni, A. *et al.* Recovery of hydrogen plasma at the sub-nanosecond timescale in a plasma-wakefield accelerator. *Commun Phys* **7**, 241 (2024)

Temperature effects in plasmas

Credit: Ibrahim Najmudin

- **Other diagnostics are necessary to detangle competing effects…**
- **Beam based diagnostics may not differentiate between e.g. a change in density and and change in temperature**

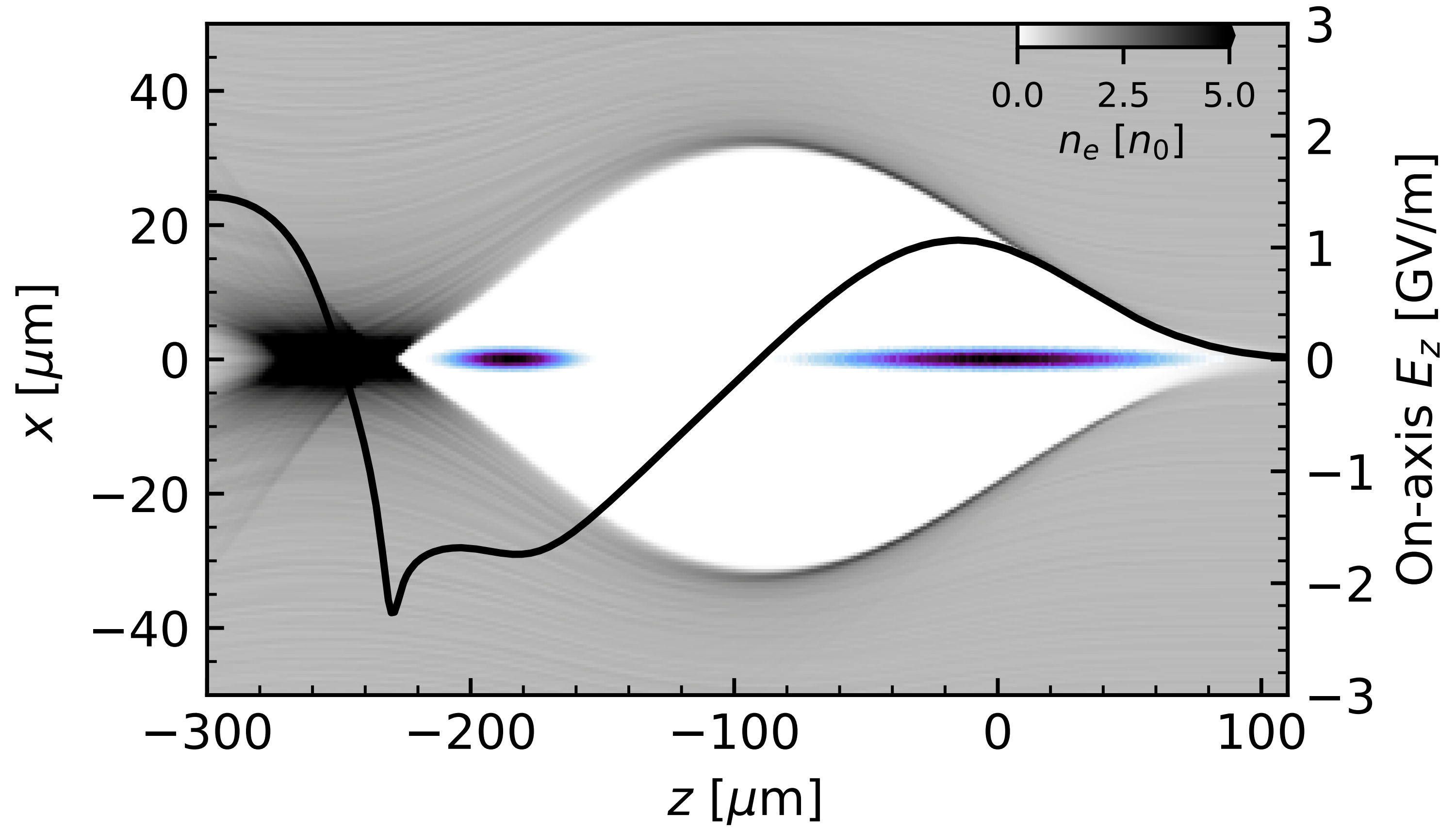


n_e = 1 x 10^{16} cm^{-3}
T_e = 1 eV

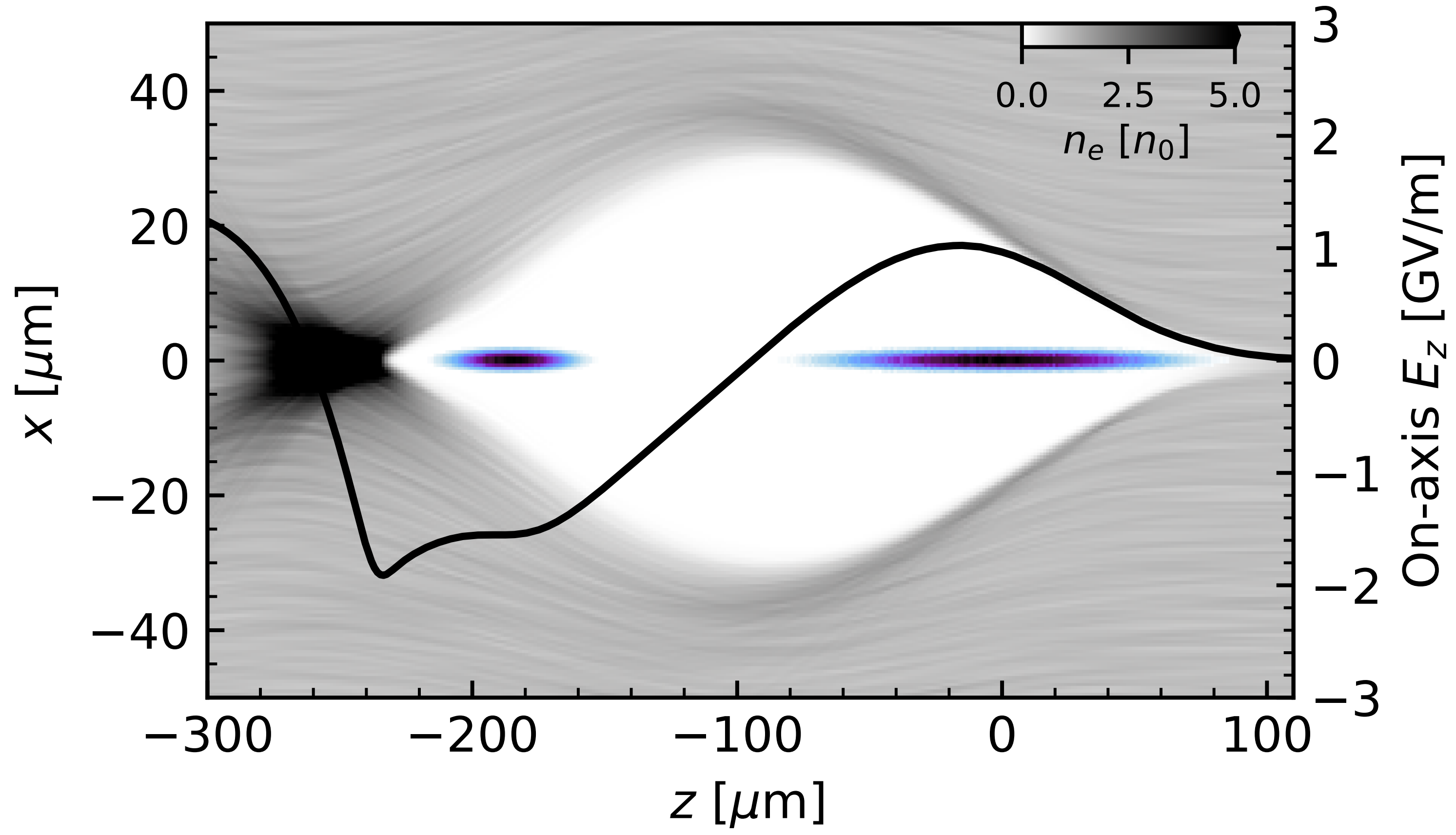
Change in density

OR

Change in temperature?



n_e = 1.10 x 10^{16} cm^{-3}
T_e = 1 eV

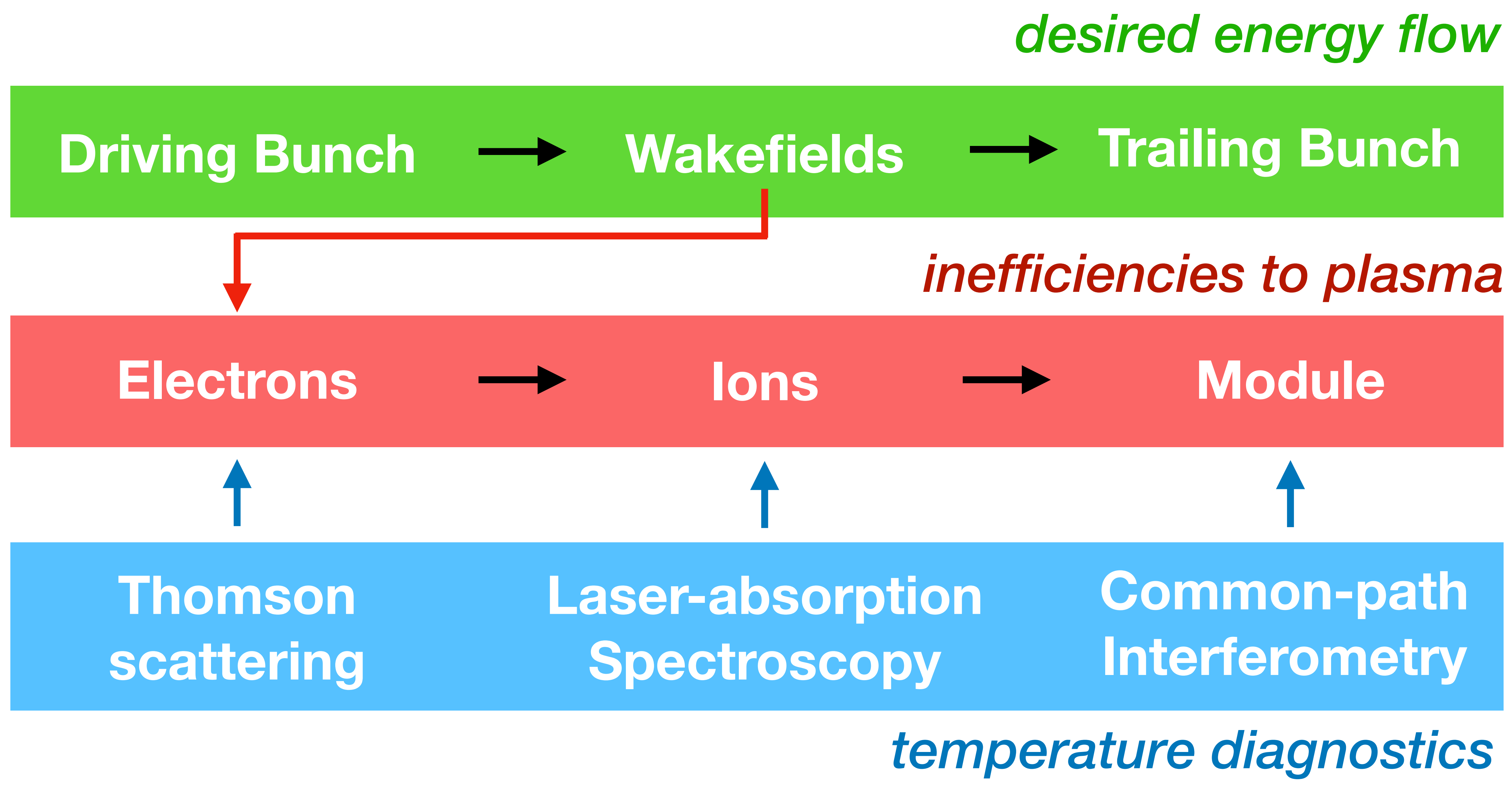


n_e = 1 x 10^{16} cm^{-3}
T_e = 100 eV

Other specialist diagnostics need to be developed to see the full picture

HiPE laboratory

- **Aim: develop tools to understand the thermodynamics of plasma accelerators**
  - Experiments and simulation
  - Simulations - Ibrahim Najmudin's talk
- **Developing a suite of diagnostics to experimentally measure temperature effects in plasma accelerators at new laboratory in Oxford - HiPE lab**
  - Map heat transport in space and time
- **Be able to transport to facilities - to observe effects of acceleration**
  - All-optical and minimally invasive; run 'parasitically'
- **What are the implications for the acceleration process in current and future accelerators?**



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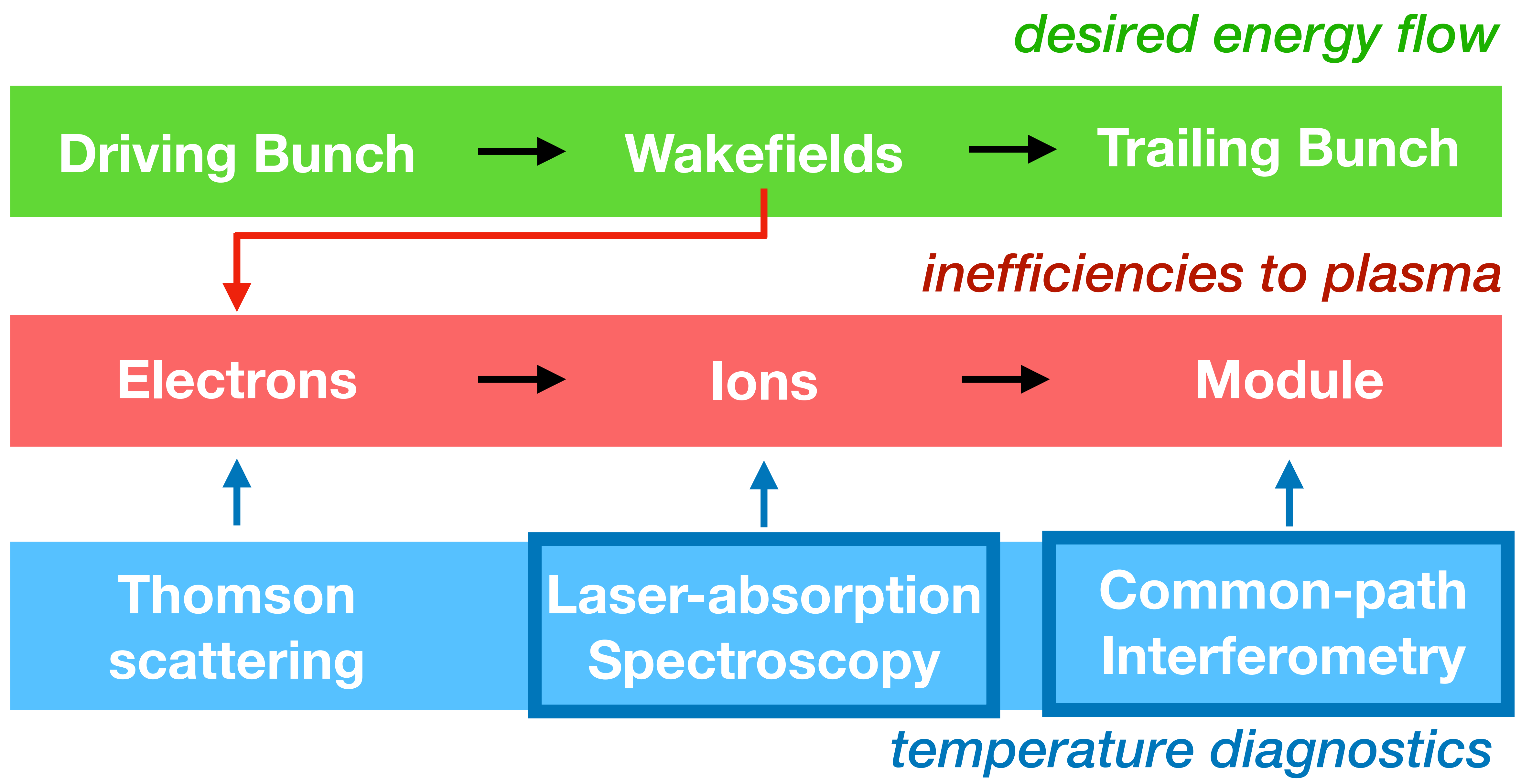
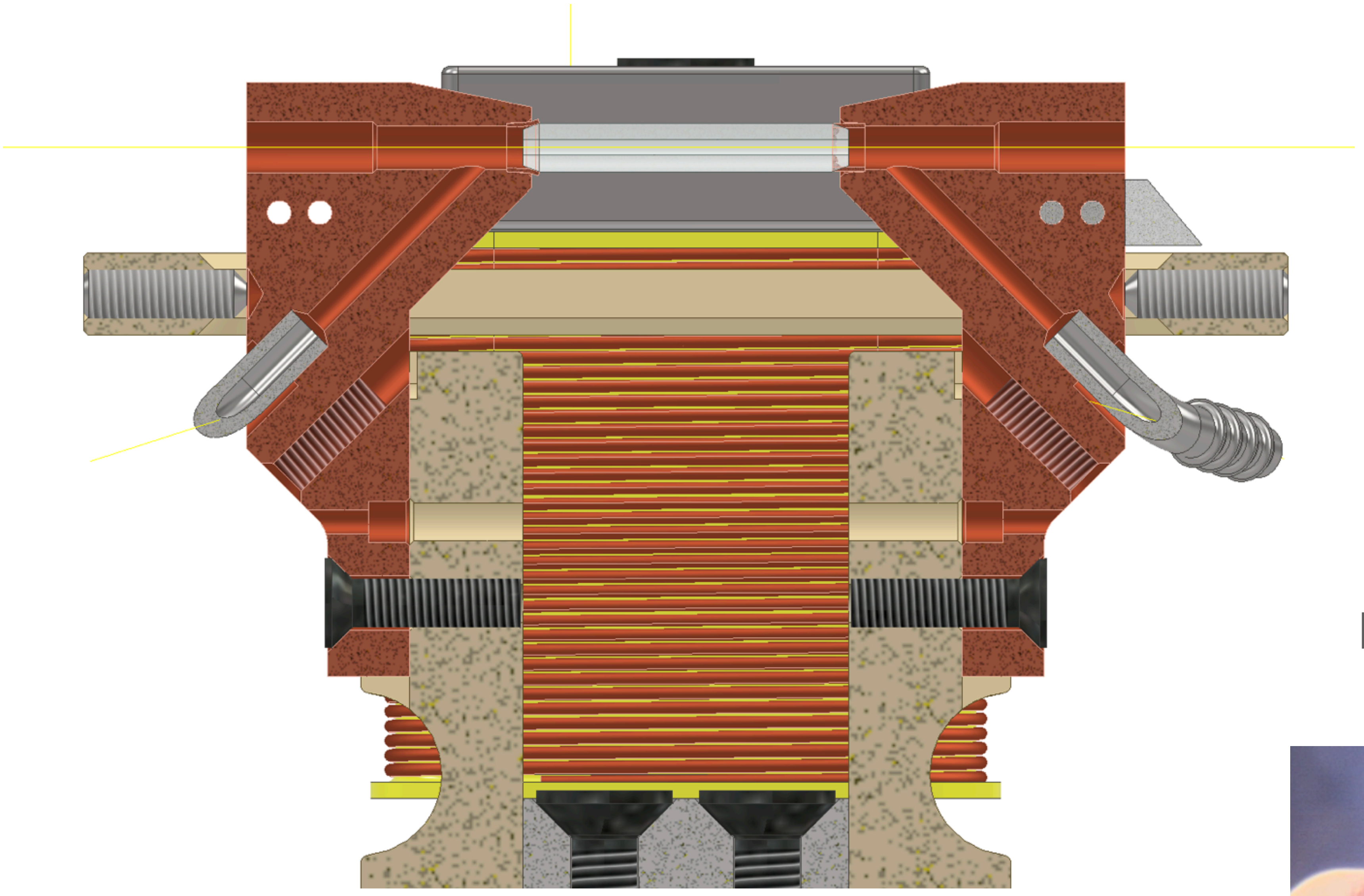


Target

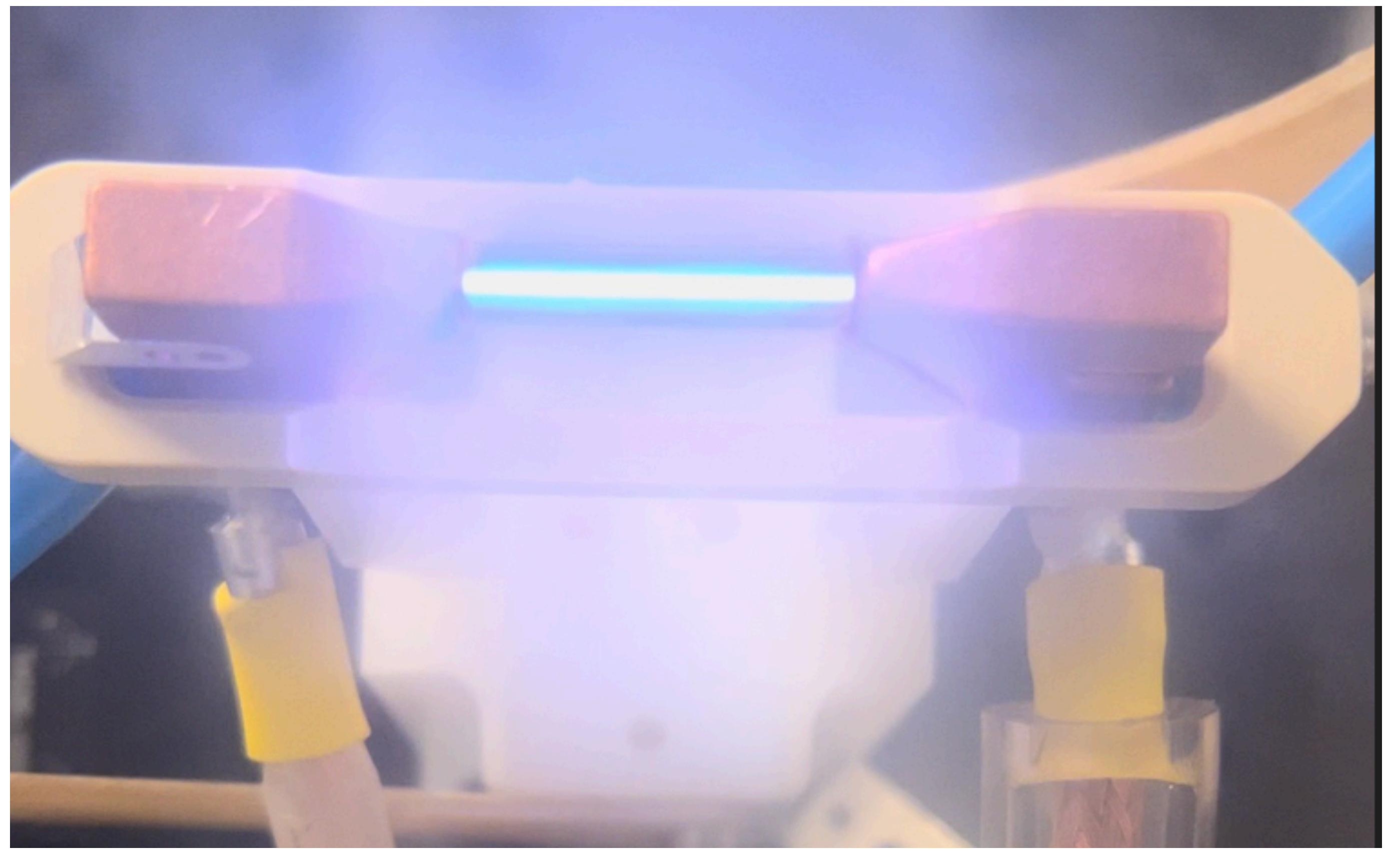
- **~1-10 mbar, optical path length 2 cm**
- **Designed by Oslo University group as plasma lens - easy change of length, material etc**
- **Cell filled via pulsed solenoid valve from argon buffer volume**
  - 2 - 10 mbar in cell
  - $n \sim 10^{17}$ cm^{-3}
  - 1 mm diameter
- **Thyratron switch based discharge:**
  - Capacitor bank charged to 10 - 20 kV
  - Repetition rate ~ 1 Hz
  - Limited by gas load on vacuum pumps



Credit: C. Linstrøm, P. Drobniak

Above: Mounted 2 cm sapphire cell

Below: Implementation in Oxford HiPE lab



Laser absorption spectroscopy

- **We expect most of the 'medium term' (microsecond scale) energy to be in the ions**
  - e.g. ion acoustic wave
  - if ions are in LTE then can infer temperature from electrons
- **Laser absorption spectroscopy (LAS) can provide a temperature measurement of any species that has a transition between energy levels that can be accessed using a narrow bandwidth laser**
- **We target transitions in excited argon (neutral or ionised) created by heating from HV discharge**
- **c.f. Optical emission spectroscopy**

Involves fewer assumptions

Can track temperature over much longer timescales/different regimes of operation

Doesn't require hydrogen

	Lower state	Upper state	Transition Wavelength (vacuum) / nm
Excited neutral (Ar I*)	4s	4p	763.721
Ionised (Ar II)	3d ^4F	4p $^2D^o$	640.098

Laser absorption spectroscopy - method

- **Laser with initial intensity I_0 travelling distance x through plasma with mass density ρ is given by**

$$I(x) = I_0 e^{-\kappa\rho x}$$

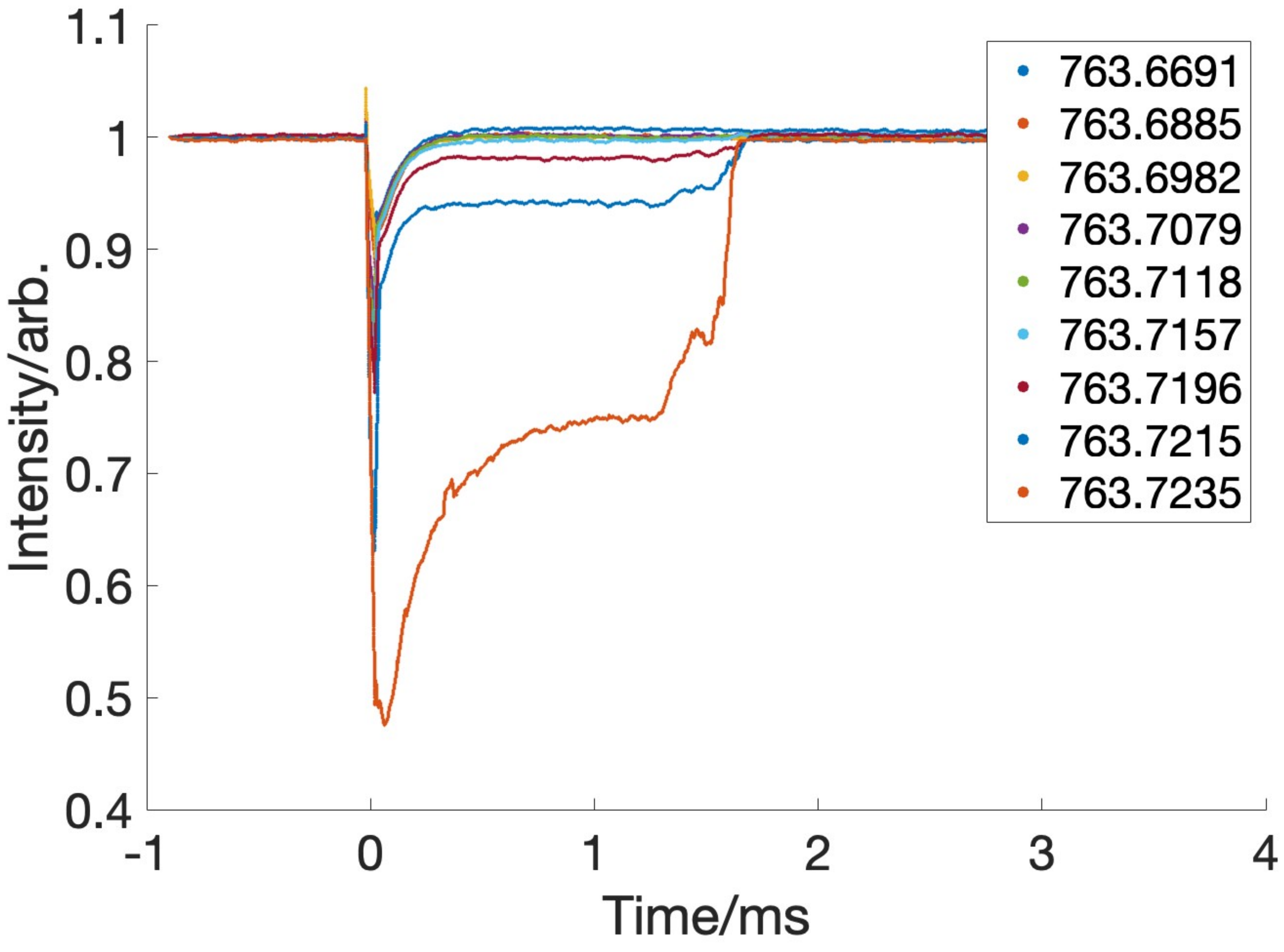
$$\text{absorption} = \ln\frac{I_0}{I} = \kappa\rho x$$

- **Due to Doppler shift, the frequency of laser absorption is dependent on the particles' velocities**
  - Gaussian broadening from temperature convolved with Lorentzian component from pressure

$$\Delta\nu_{FWHM} = \frac{1}{\lambda_0}\sqrt{\frac{8k_B T \ln(2)}{m}}$$

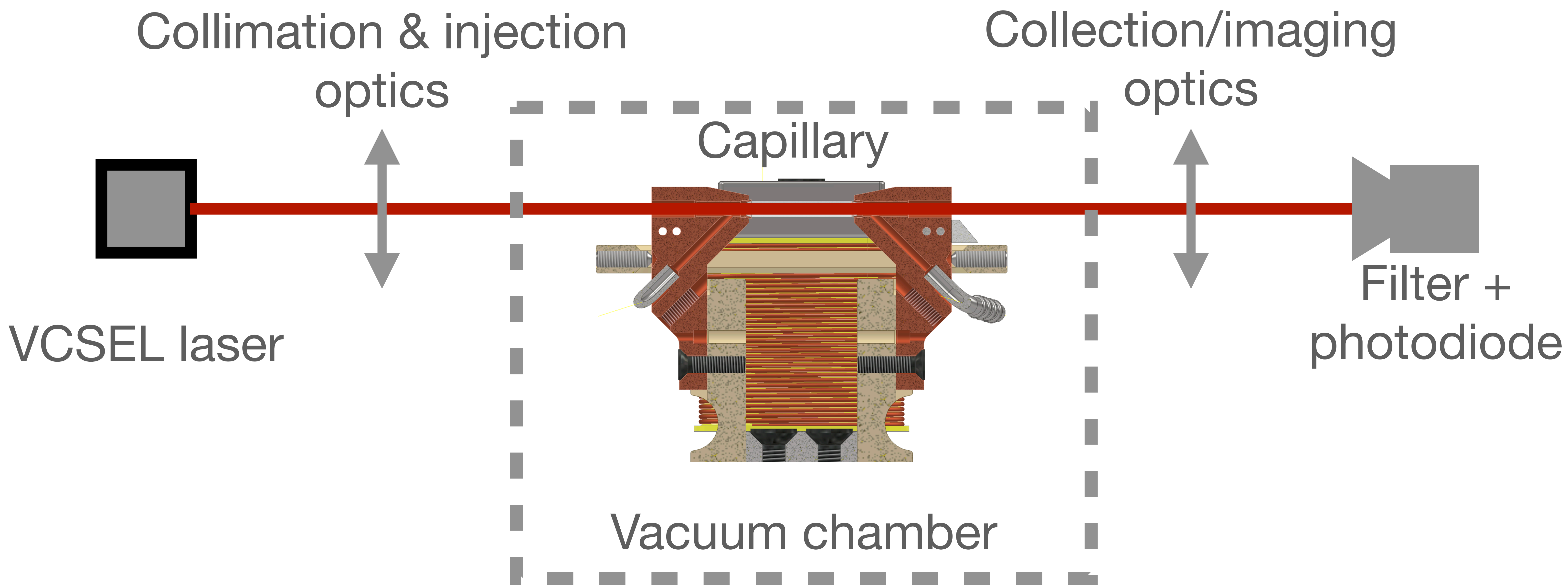
  - Laser bandwidth << broadened line width
  - Time-resolved measurement limited by:
    - State lifetime
    - Photodiode & oscilloscope speed, electrical noise

25 mbar Argon absorption with diode wavelength (nm)



Laser absorption spectroscopy - method

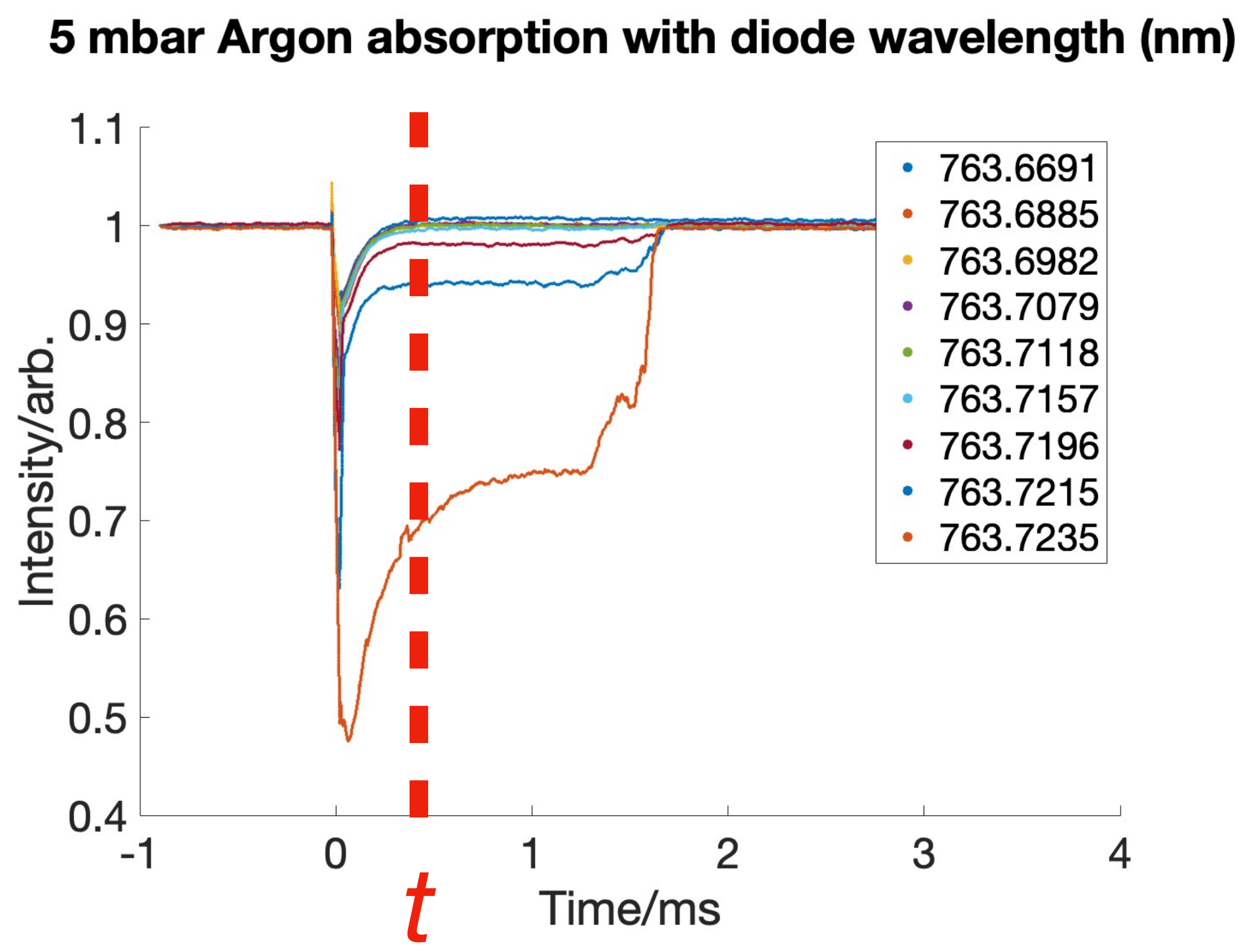
> ~10 mbar, optical path length 2 cm

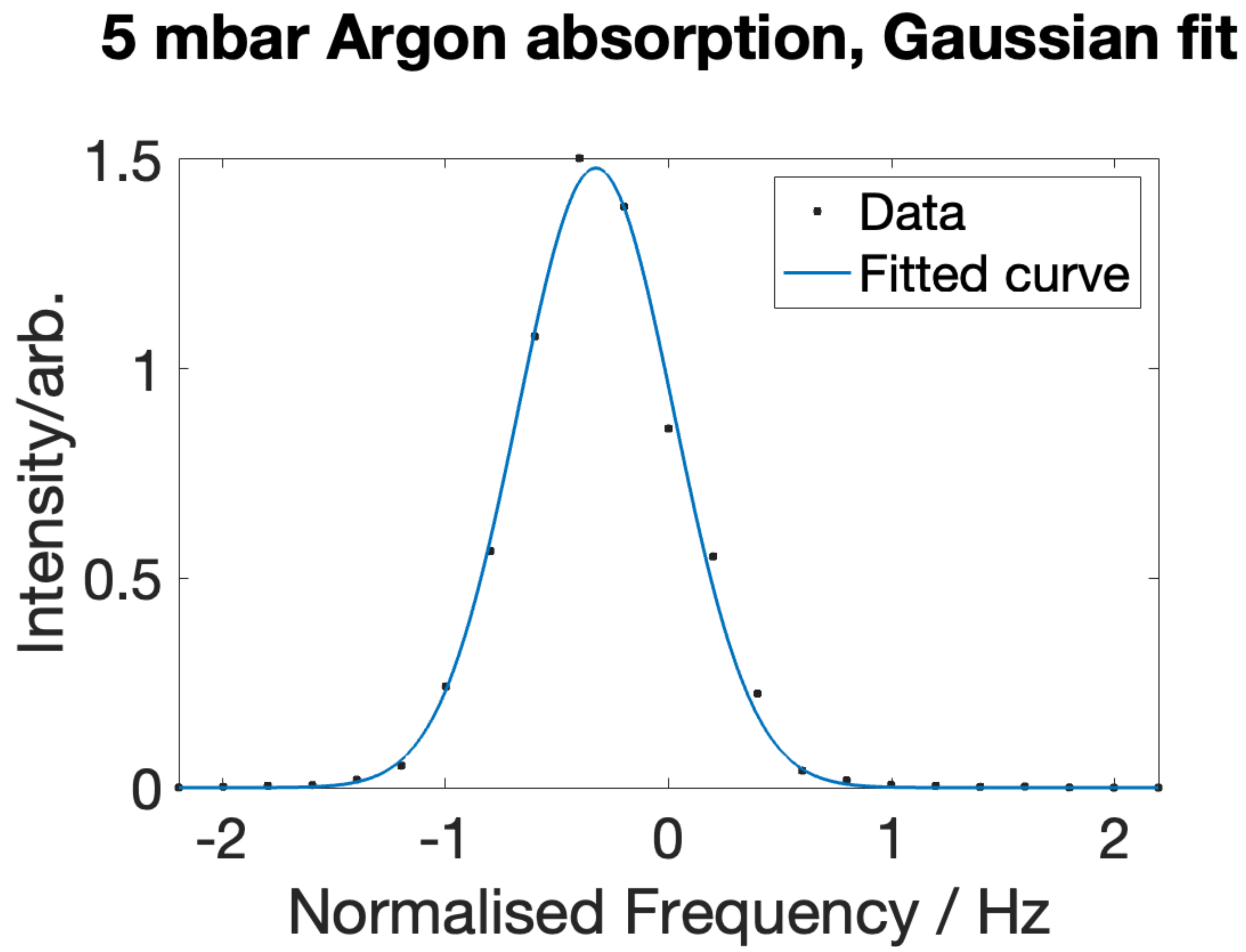


Laser absorption spectroscopy - results

Trace acquisition and analysis process

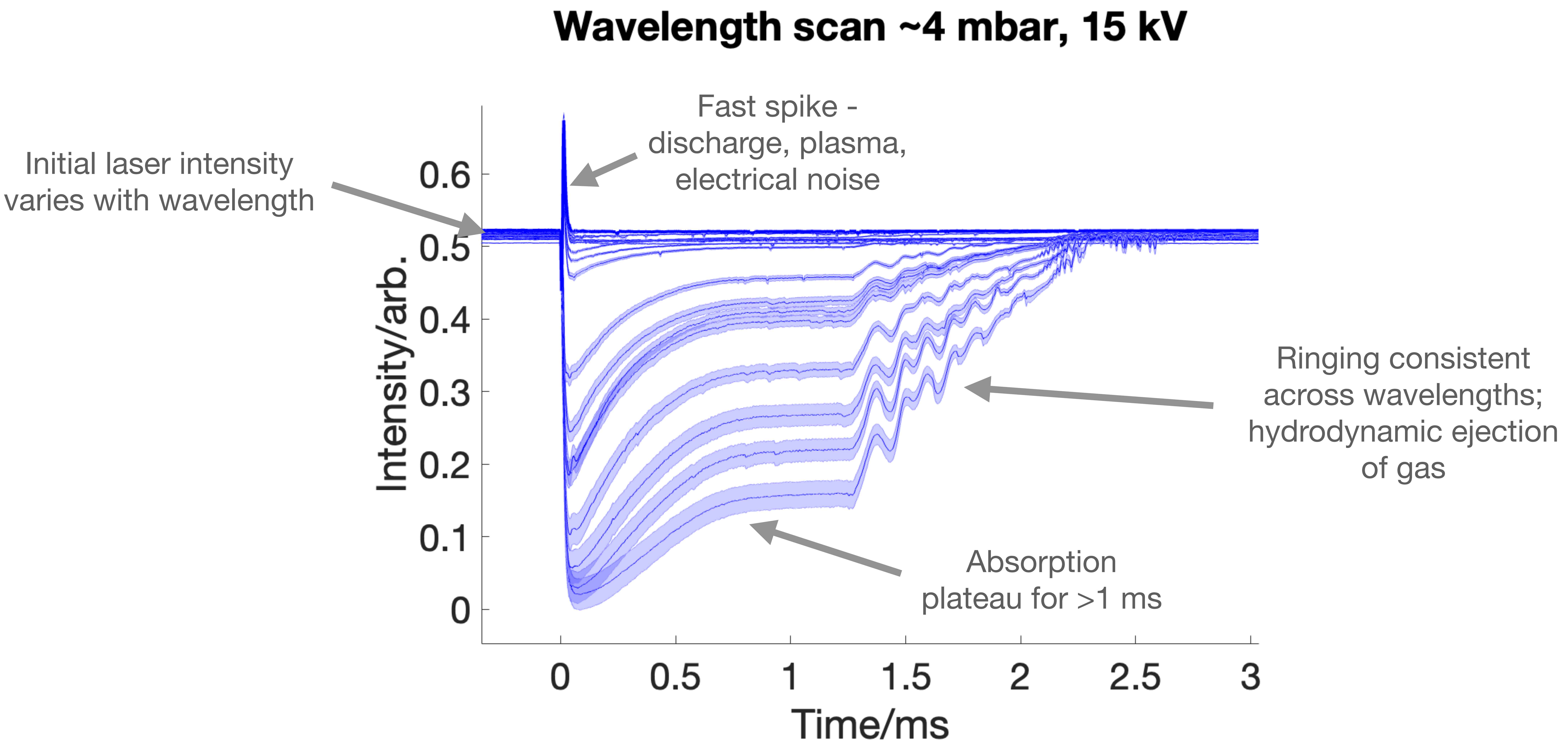
- **20-100 shots per wavelength; average photodiode output into a single trace**
- **Convert -> absorption**
- **Absorption vs. frequency at each time slice *t***
  - VCSEL calibration converts diode current to wavelength output
- **Fit Voight profile with free parameters:**
  - Amplitude, FWHM, position of Gaussian, Lorentzian
- **Convert Gaussian FWHM to temperature**





Laser absorption spectroscopy - results

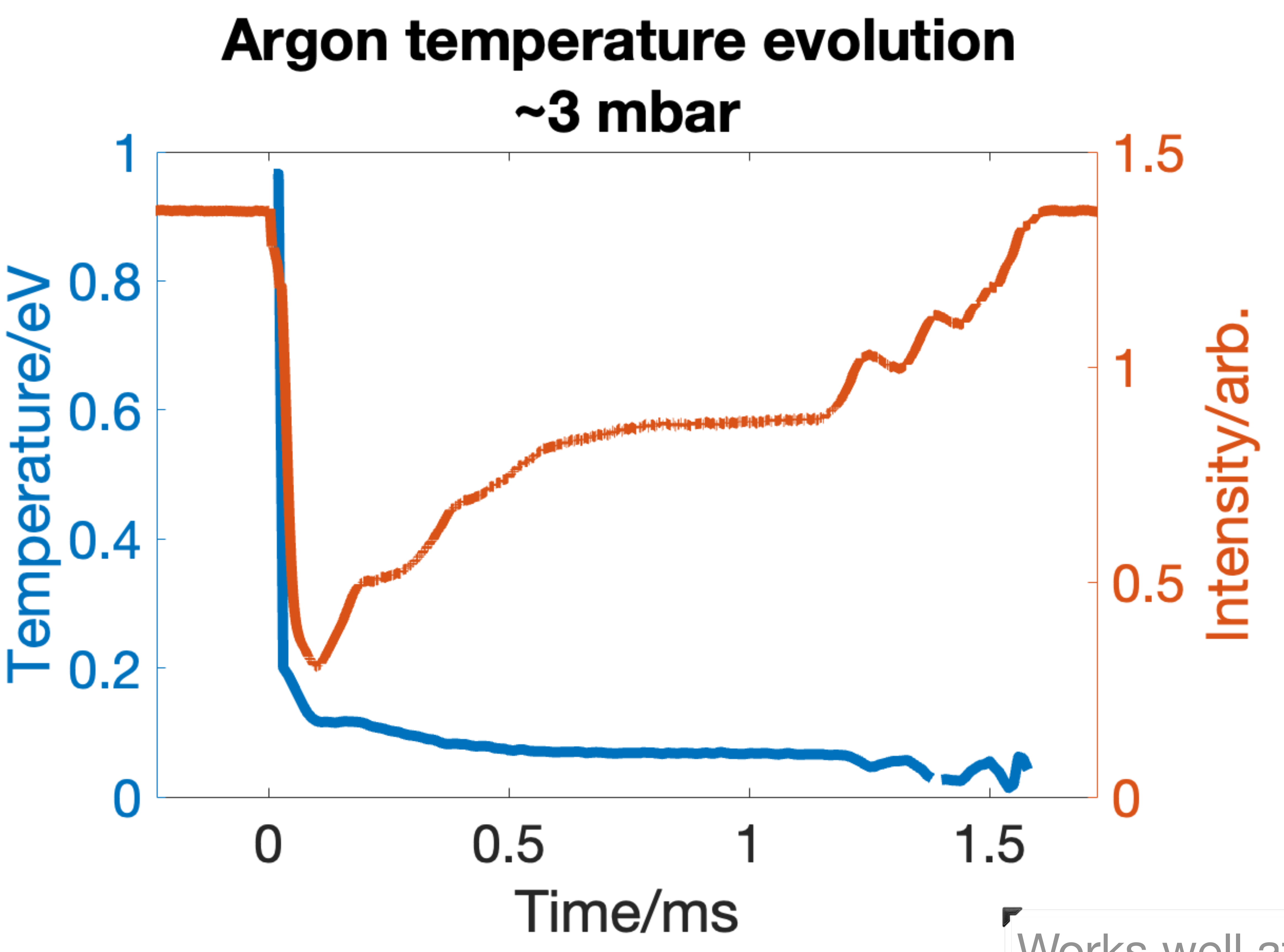
Wavelength scan - features

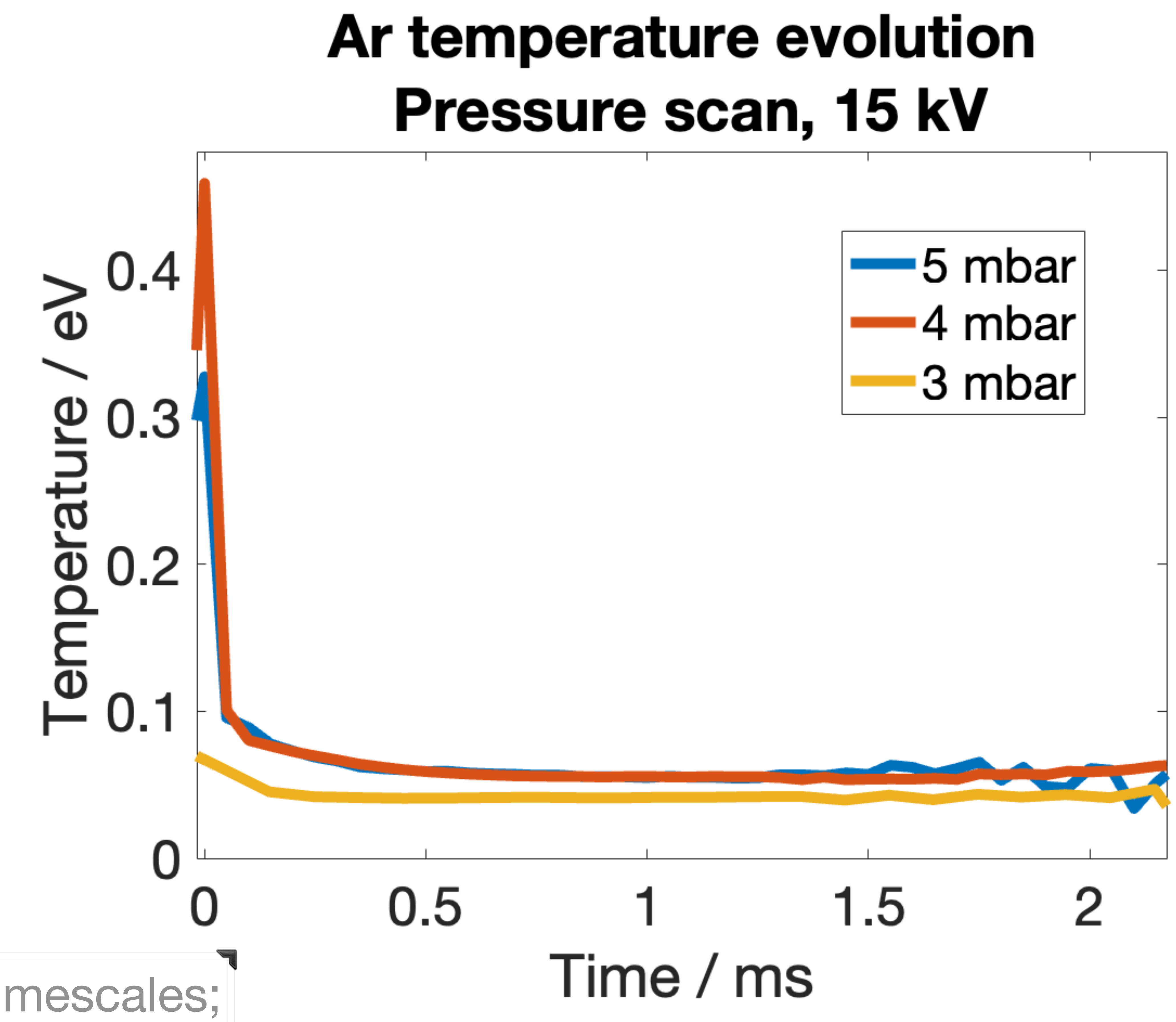


Laser absorption spectroscopy - results

Temperature extraction

Provisional

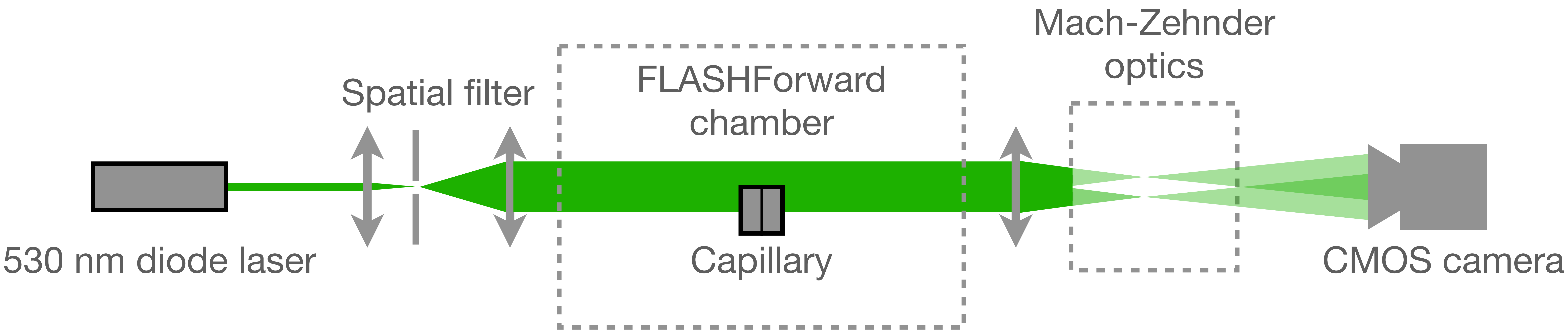




Works well at long timescales;
< 10 microsecond difficult

Plasma cell temperature diagnostic

- Sapphire capillary expands as it heats - increasing optical path length
- CW laser used as probe to relate a (calibrated) phase shift to a temperature change

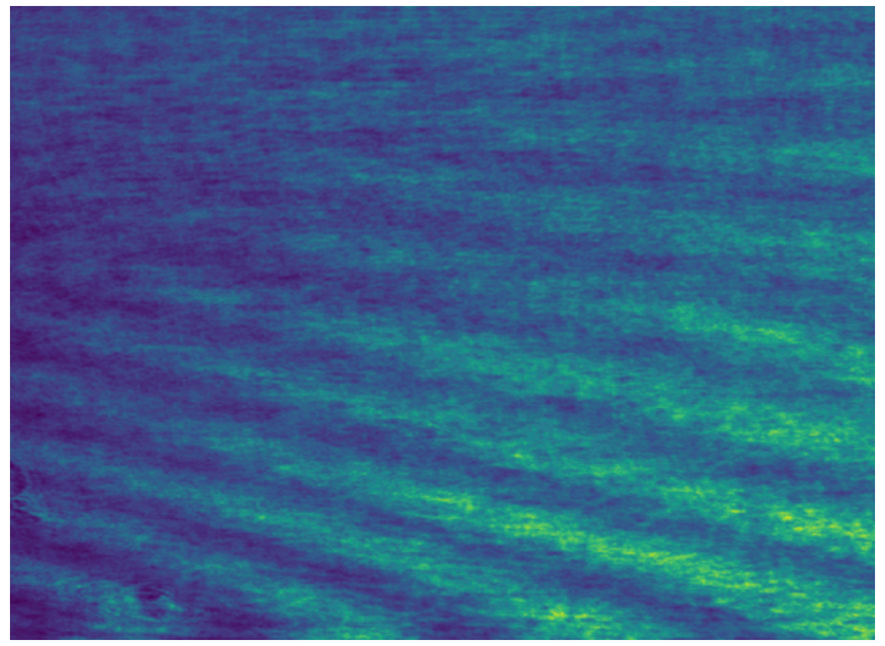


- Common optical path interferometer reduces vibrations & noise; totally non-invasive measurement
- Bottom half of laser beam passes through the capillary (probe); the top half through vacuum (reference).
- Beamsplitters create a copy of the beam and shift one copy onto the other, creating an interference pattern.
- Changes in phase result in shifting fringes on camera.

Plasma cell temperature diagnostic - data

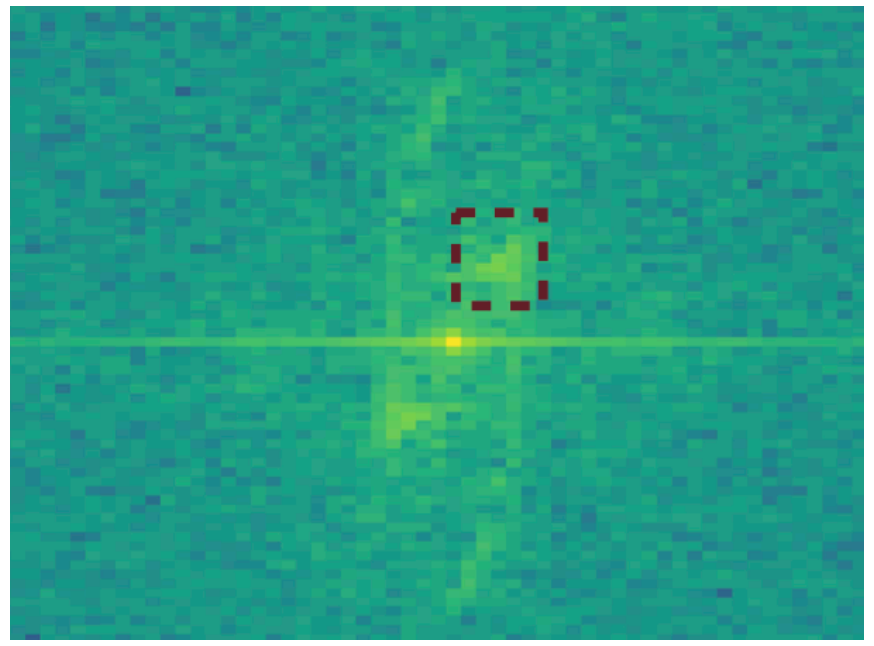
- **The analysis follows standard interferometric methods**
  - This allows for a 2D time-evolving map of the cell temperature to be extracted, over the area covered by the probe beam.
- **Alternatively a radial line out of the capillary can be taken and consecutive shots plotted at a waterfall to quickly visualise the phase shift:**

Cropped raw data



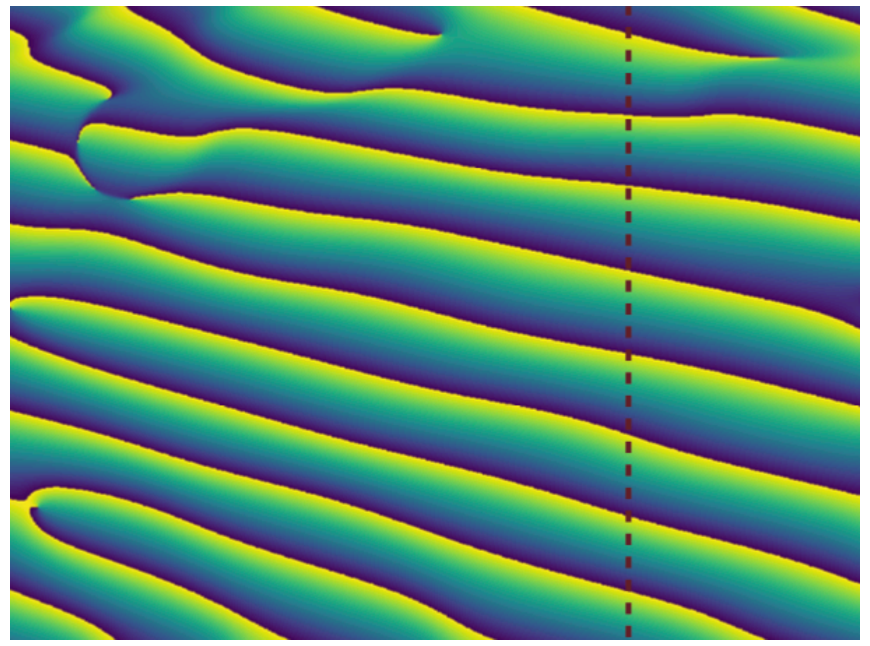
Credit: Ibrahim Najmudin

Fourier transform; filter frequencies

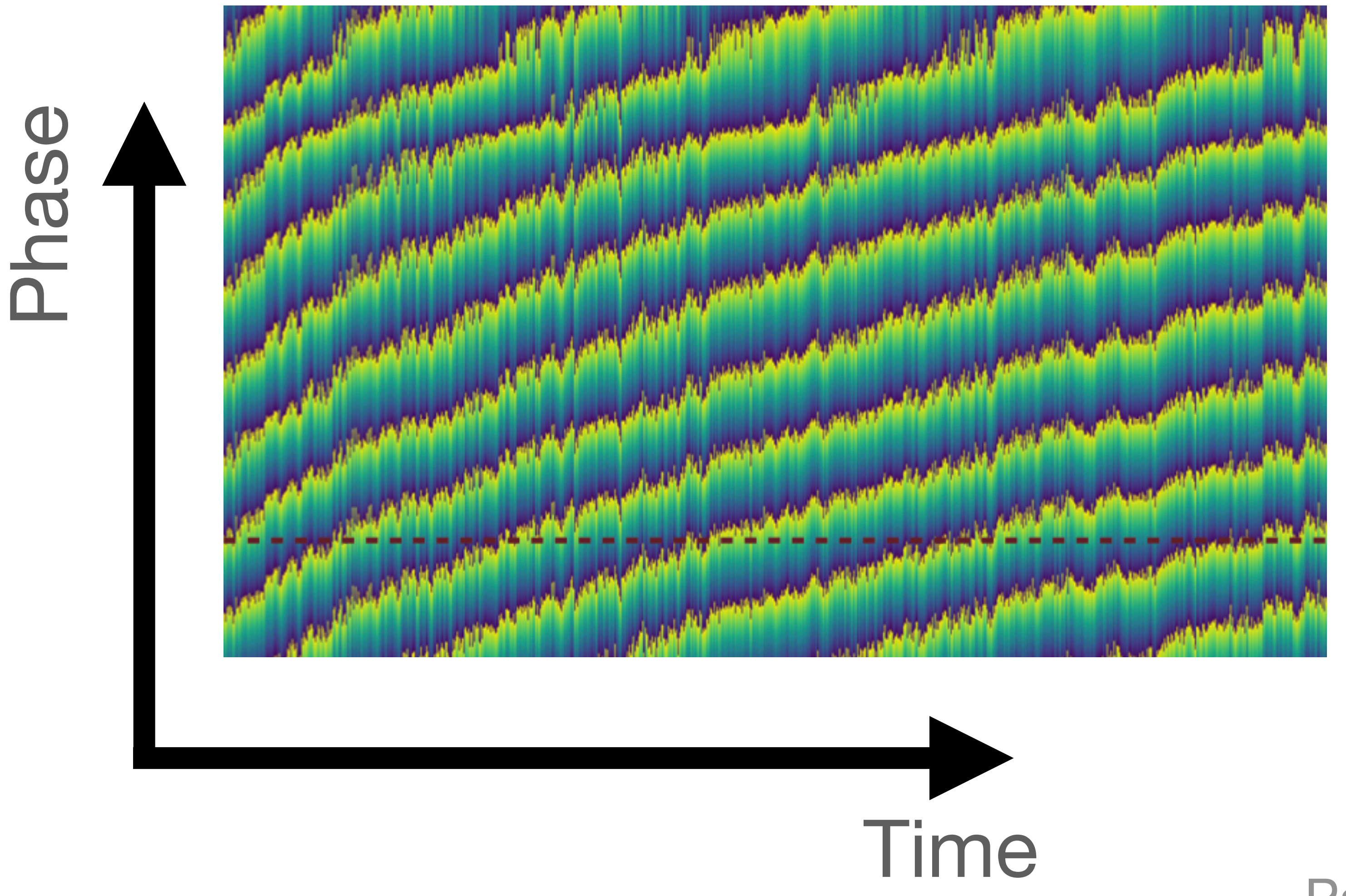


Inverse Fourier transform

Take single radial slice from image

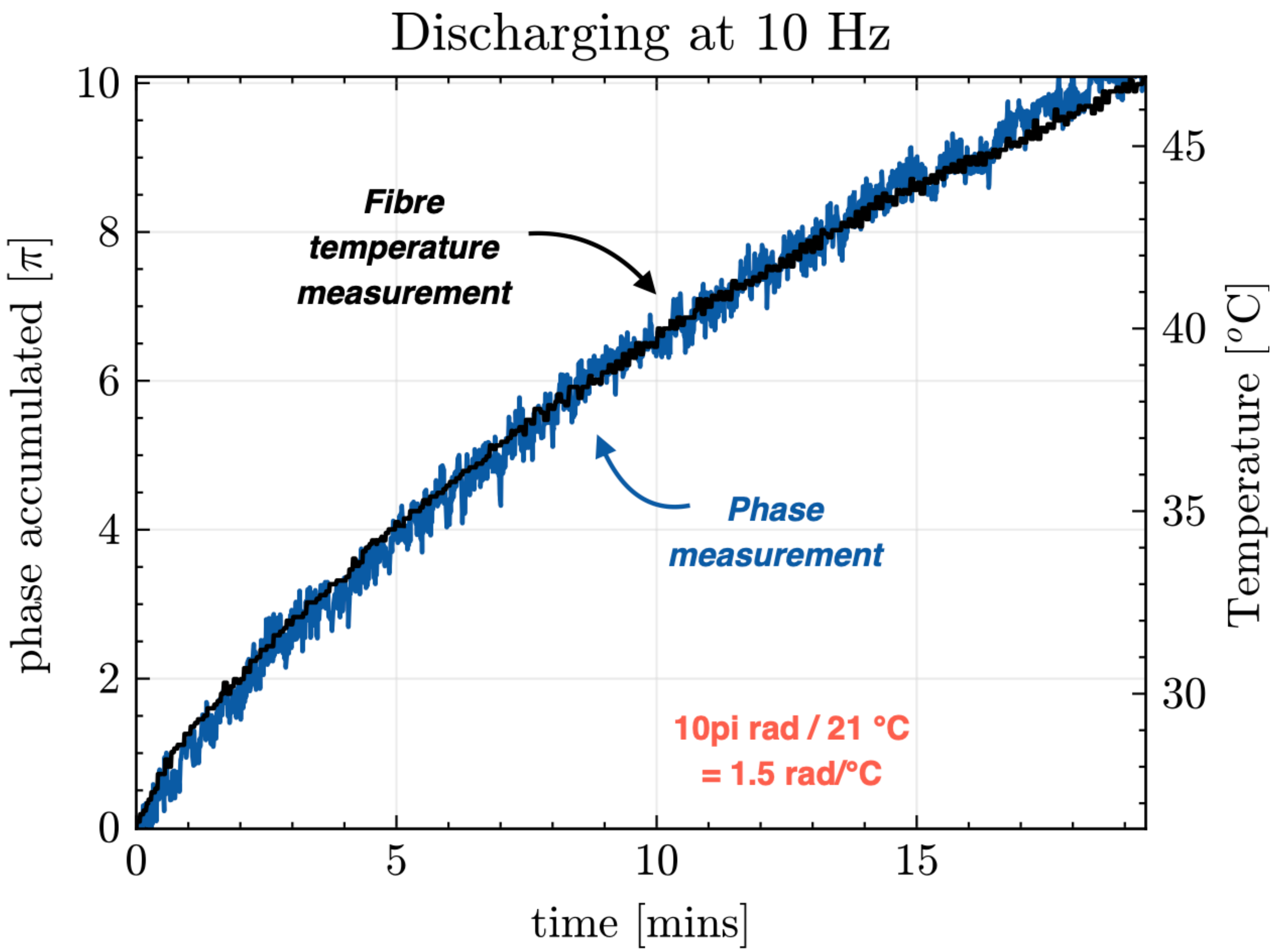


Plot slice from time array of images to make waterfall showing time evolution of fringes



Plasma cell temperature diagnostic - data

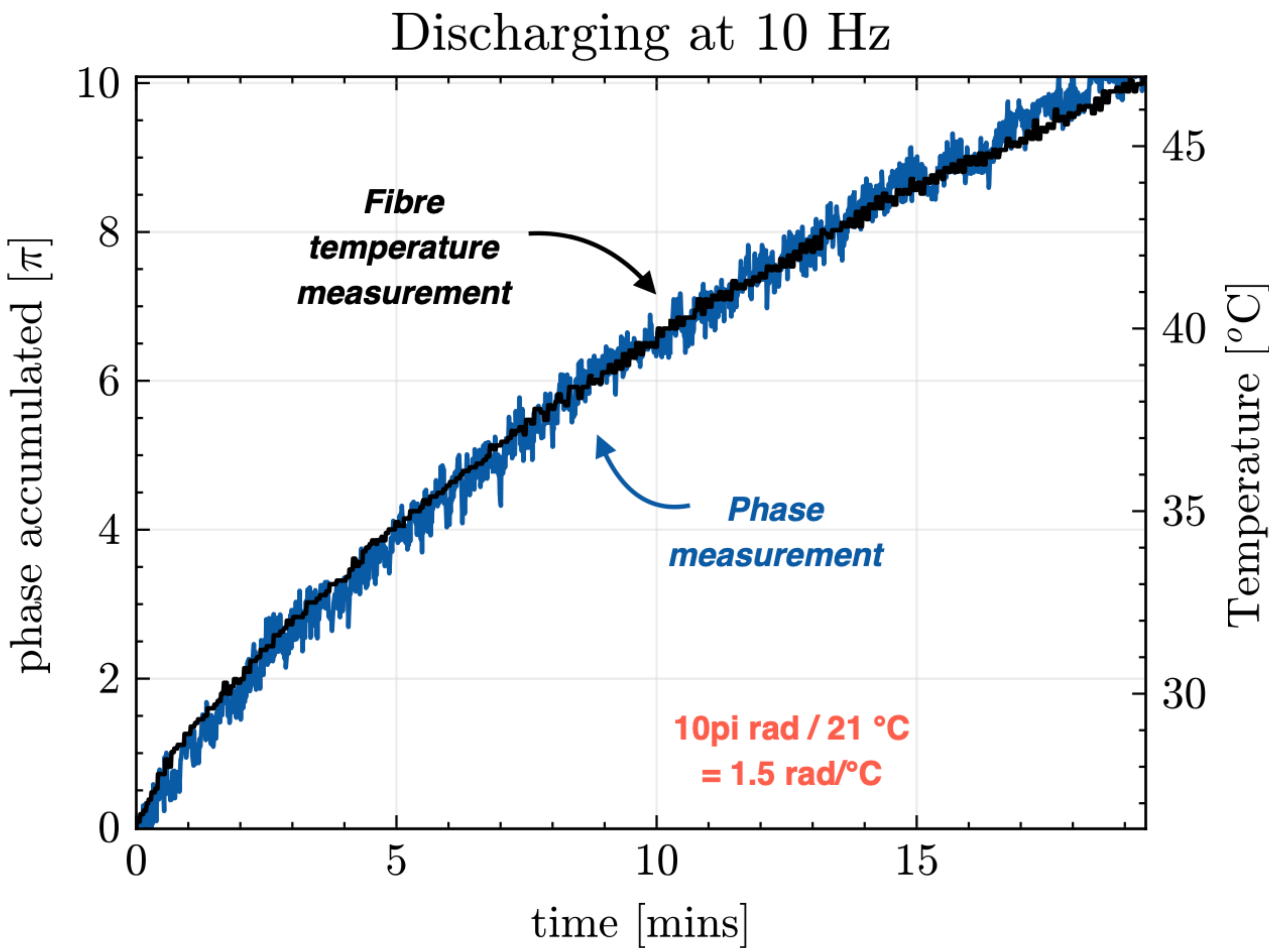
- **Diagnostic was calibrated for capillaries used at FLASHForward in the DESY ADVANCE lab**
  - Calibration needs to be performed on an identical capillary to produce an accurate phase shift to temperature change mapping
- **Capillary heated high-repetition rate discharge to calibrate phase shift to temperature change.**
- **As capillary heated, temperature measured using PT1000 probes and fibre-optic thermometer; compared with the phase accumulated.**
- **Notes:**
  - Can only determine temperature change
  - Requires knowledge of initial temperature (room temperature) and constant tracking



Plasma cell temperature diagnostic - data

- **Outlook**
  - Ability to determine missing energy channels
  - Calculation of efficiencies
  - Will determine if active cooling is required

- **More experiments in an accelerator need to be done to determine the above**



Conclusions

- The heat flow and temperature changes that occur in plasma accelerators could potentially place fundamental limits on aspects of their performance e.g. repetition rate.
- New diagnostics are required in order to provide a full understanding of the deposition and transport of heat during and after the acceleration events
- The range of timescales involved makes simulations difficult, and experiments may have to lead the charge.
- We are developing diagnostics for time-resolved ion and electron temperature and density throughout the discharge and acceleration process, as well as monitoring the cell temperature.
  - Non-invasive (all-optical), able to operate in parallel at facilities.