Considerations for high repetition rate plasma accelerator sources

Advanced diagnostics for MHz-repetition-rate plasma accelerator sources

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HELMHOLTZ

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

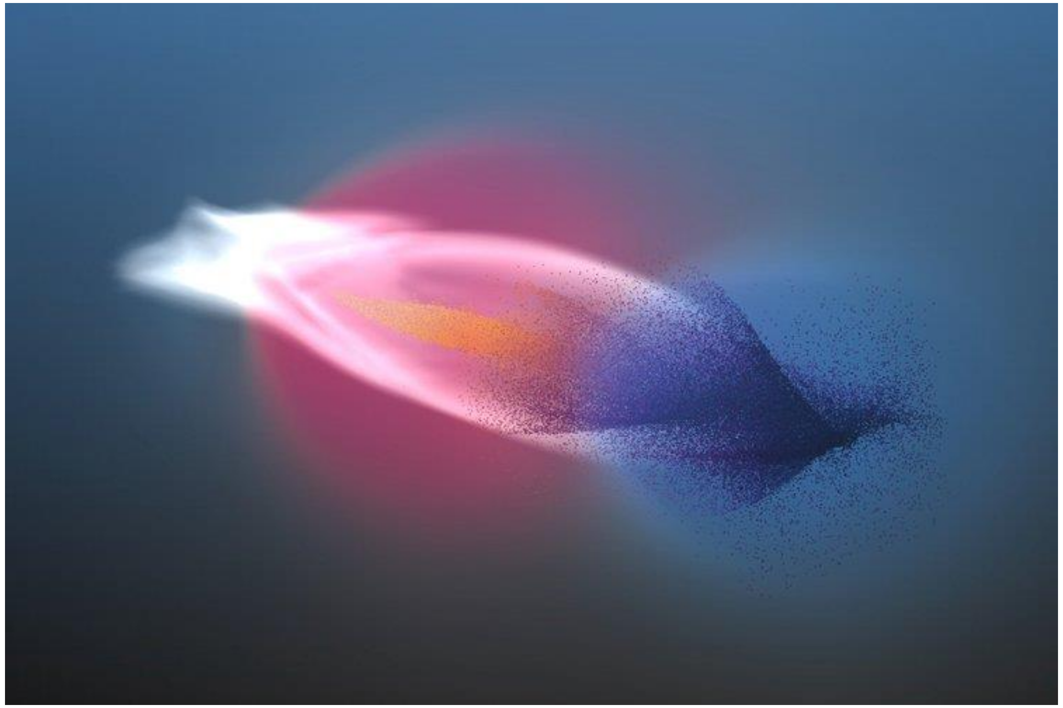
DESY.

Motivation

Advanced diagnostics for MHz-repetition-rate plasma accelerator sources

- Plasma-Wakefield accelerator promises to be a compact and cost-effective energy booster for electron linacs

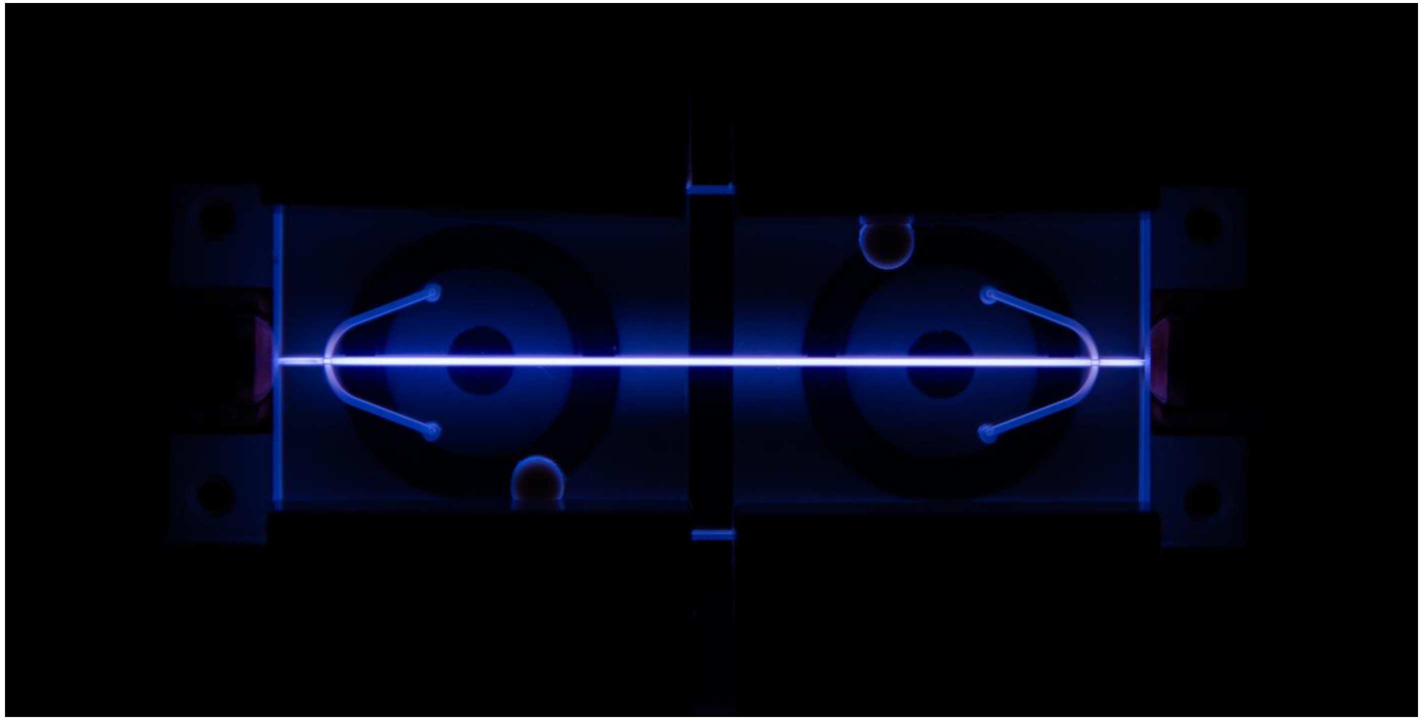
- FLASHForward facility at DESY has demonstrated accelerated electron bunches can maintain charge, energy spread and emittance during plasma acceleration.



Motivation

Advanced diagnostics for MHz-repetition-rate plasma accelerator sources

- MHz frequencies are necessary in order to match bunch patterns of superconducting RF Linacs.
- Two challenges: plasma density stability. High heat loads into the capillary.



Motivation

Advanced diagnostics for MHz-repetition-rate plasma accelerator sources

- **Plasma density measurements**
  - Ultrahigh-temporal-resolution interferometry diagnostic will be applied to this problem, to study the evolution of the plasma density in this target. (nanosecond resolution)

- **Cell Temperature Studies**
  - Long-term heating of the plasma cell from repeated plasma creation events with a view towards implementing mitigation strategies.

Motivation

Plasma density measurements

- We often don’t know the plasma profile very well. Current methods of measuring density have limitations:

- Optical Emission Spectroscopy (OES) Hα:
  - Assumes a given temperature.
  - No spatial resolution (No radial profiles)

- Full characterization wish list:

  - Temporal evolution of density
  - Longitudinal density of capillary
  - Radial density

  - Density range of $n_e = 10^{14}$ cm^-3

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- **First Goal:**
  - To establish a two color interferometer for the purposes of measuring the density profiles of capillaries with improved sensitivity and temporal evolution.

Plasma density measurements

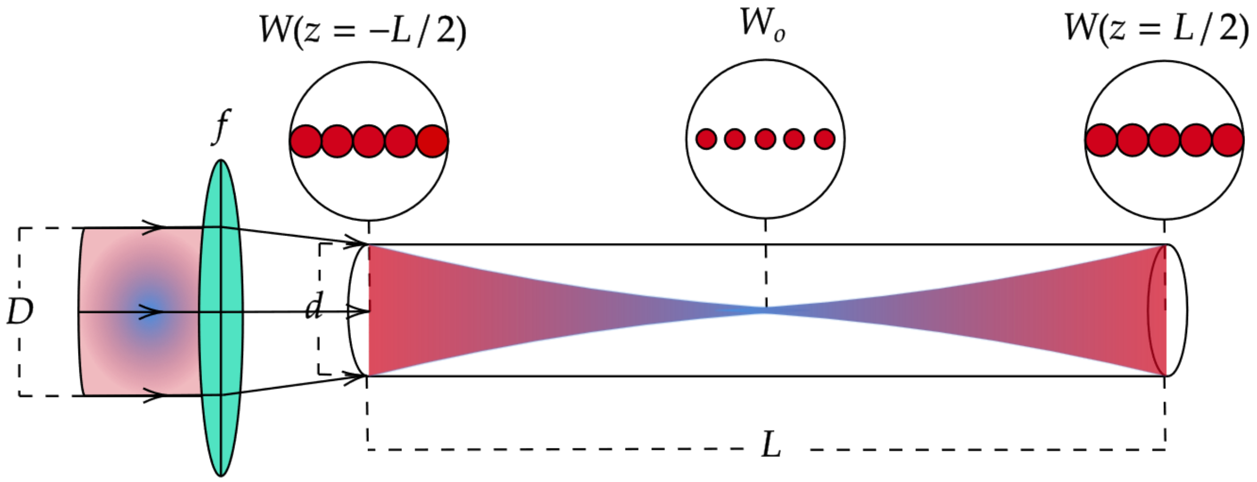
Two Color Interferometry (TCI)

- TCI:
  - Ultra-high temporal resolution interferometry
  - Spatial resolution.
  - One common beam path: much more stable (no de-coupled mirror reflections)

  - Good sensitivity: $\Phi \sim 2 \text{ x } 10^{15}$ cm^{-2}

- Possible issues: Need enough intensity to generate blue

- Integrates along the length of the plasma



Two color laser interferometry

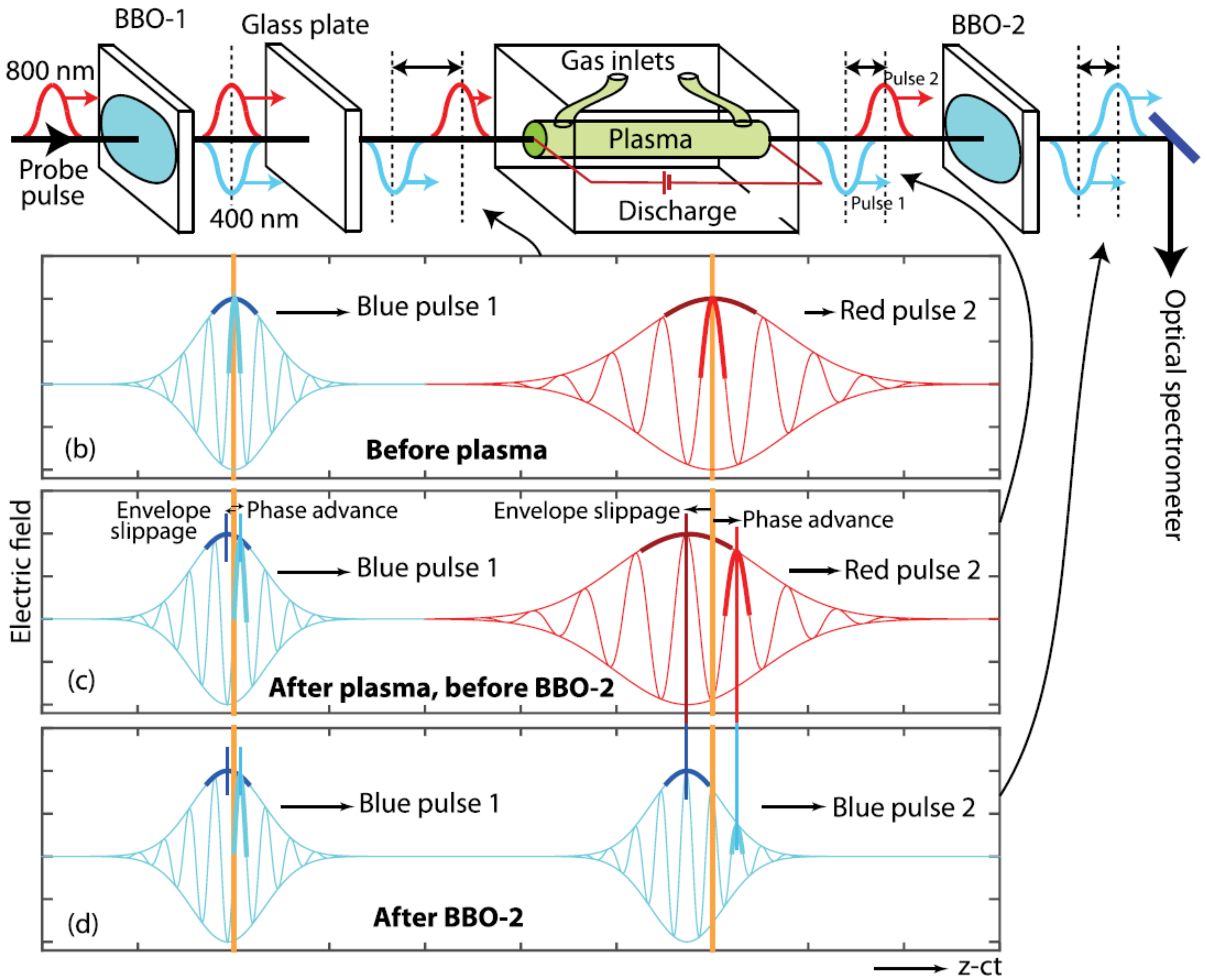
1. Barium Borate (BBO) – non linear crystal used to frequency double 800 nm into 400 nm

2. Glass to separate the pulses via dispersion

3. Plasma capillary

4. BBO again

5. Spectrometer



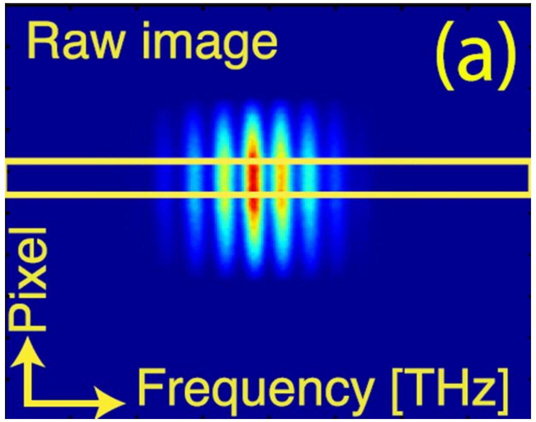
J. van Tilborg et al, *Phys. Plasmas,* 26 (2): 023106 (2019)

Two color laser interferometry

Two different flavors of TCI

Time offset

- $$\Delta t \approx \frac{L}{c}\left(\frac{3\omega_p^2}{8\omega^2}\right)$$



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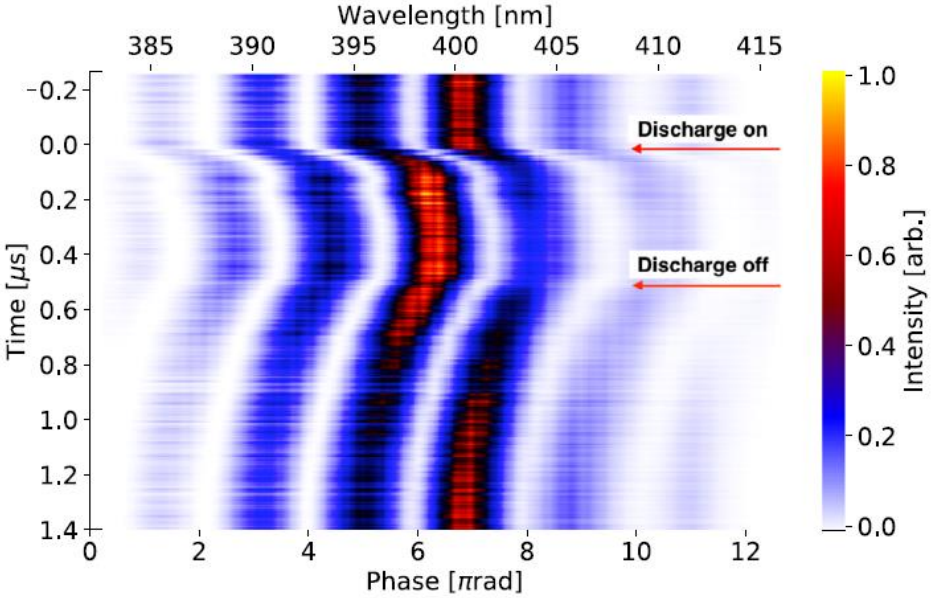

J. M. Garland et al, Rev. Sci. Instrum., 92 (1): 013505 (2021)

$$\eta = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} \qquad \omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

$$\Delta\phi = \frac{3\omega_p^2 L}{4c\omega} \longrightarrow \mathrm{n_e} = \frac{4\epsilon_0 m_e c}{3e^2}\frac{\omega}{L}\Delta\phi$$

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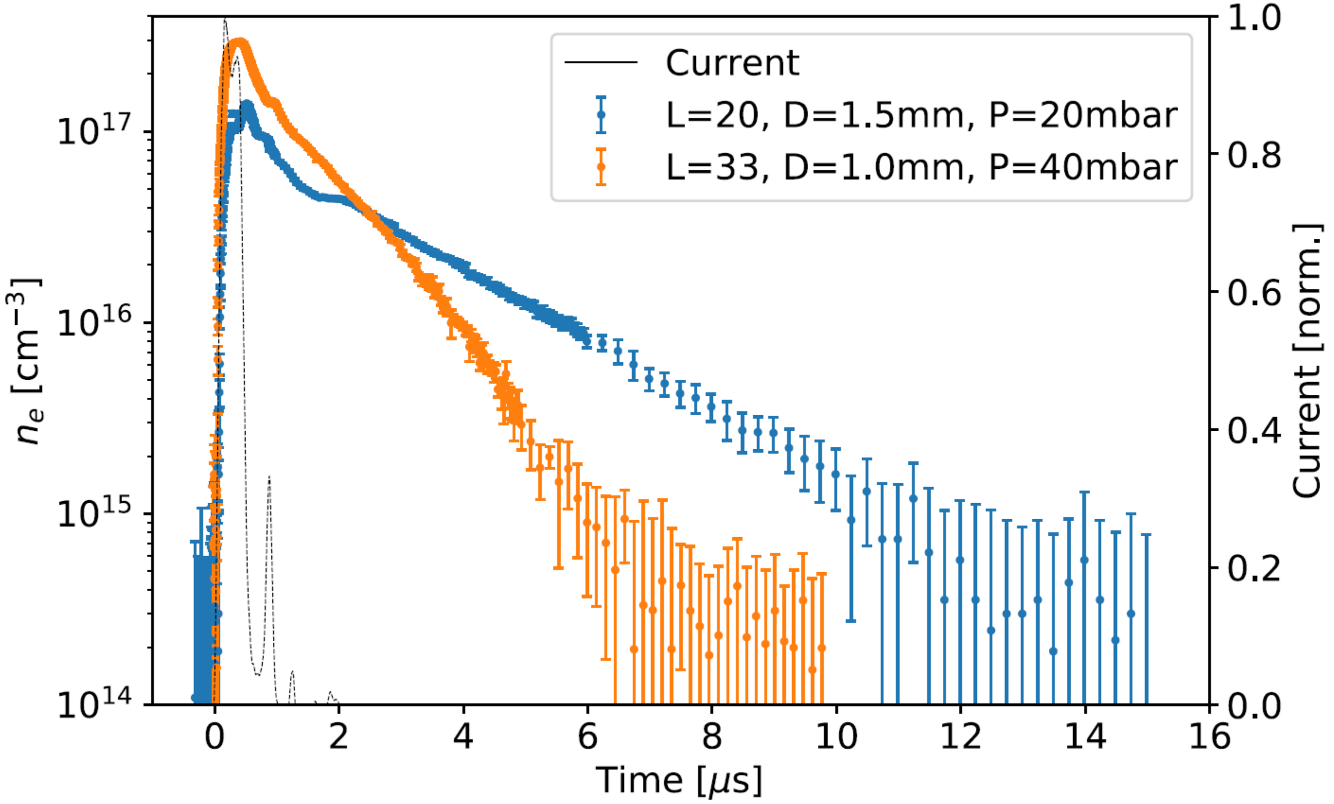

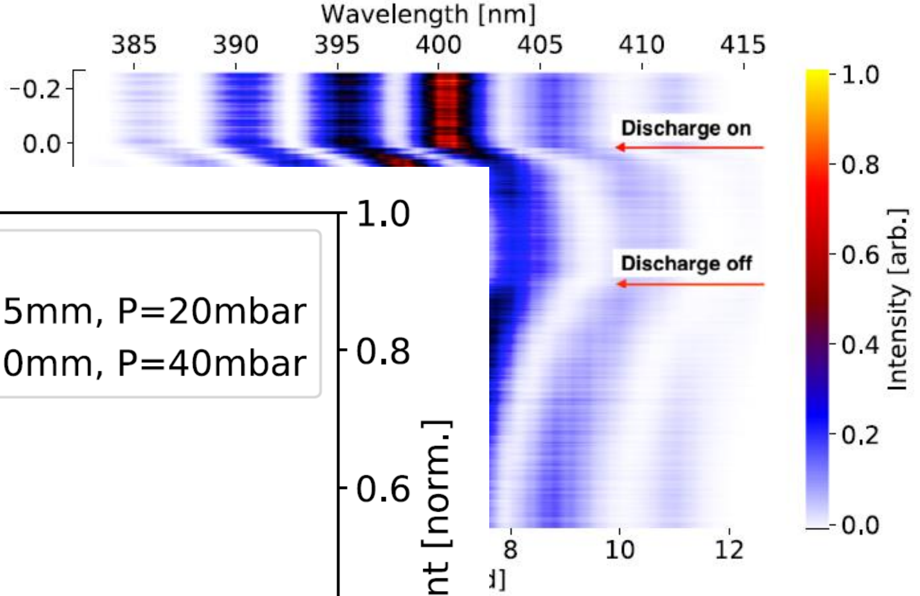

v. Sci. Instrum., 92 (1):

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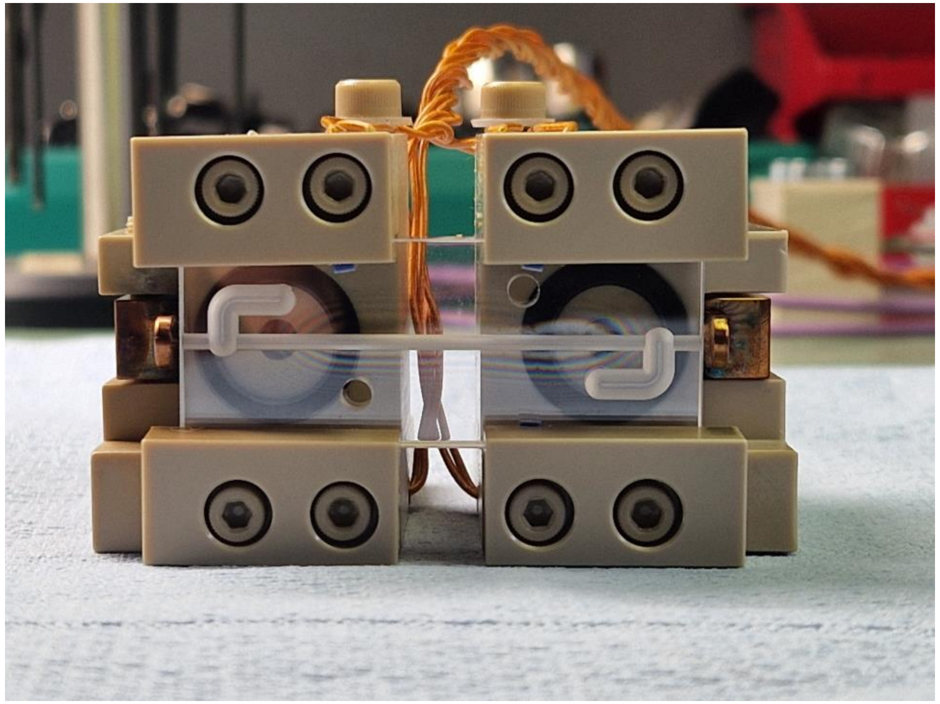
Temperature Measurements

Cell Temperature Studies

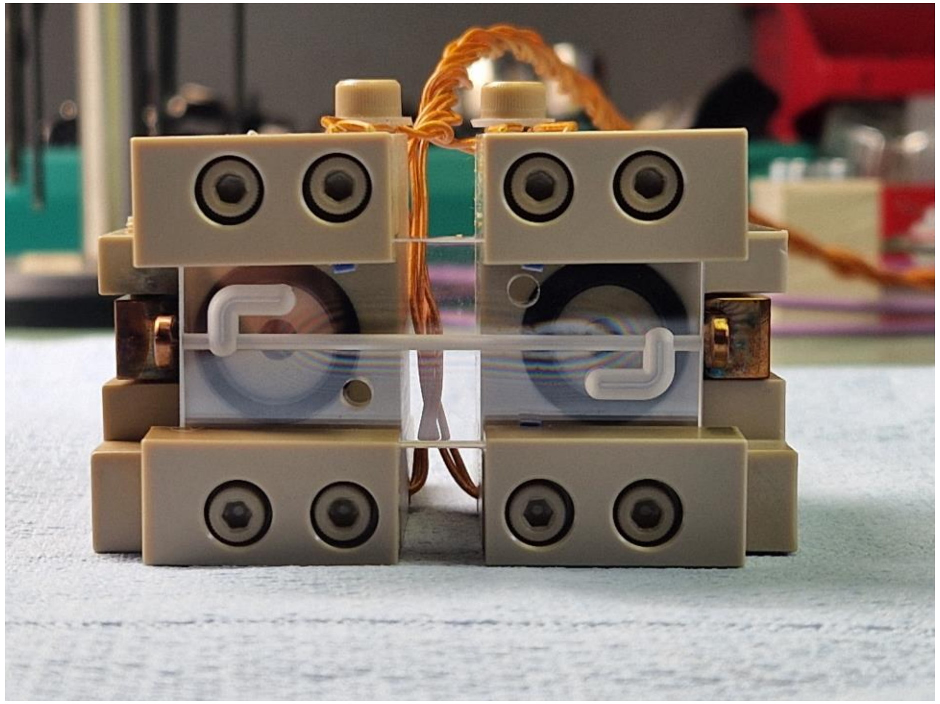
- We want capillaries of average power depositions with kHz to MHz rep. rates for FEL
  - Scale the temp measurements to design cooller cells



Temperature Measurements

Cell Temperature Studies

- Two tipes of diagnostics:
  - PT1000: Temperature dependent resistors.
  - Fiber optics: Galium Arsenide (GaAs) semiconductor crystal. Temperature dependence of the bandgap of GaAs



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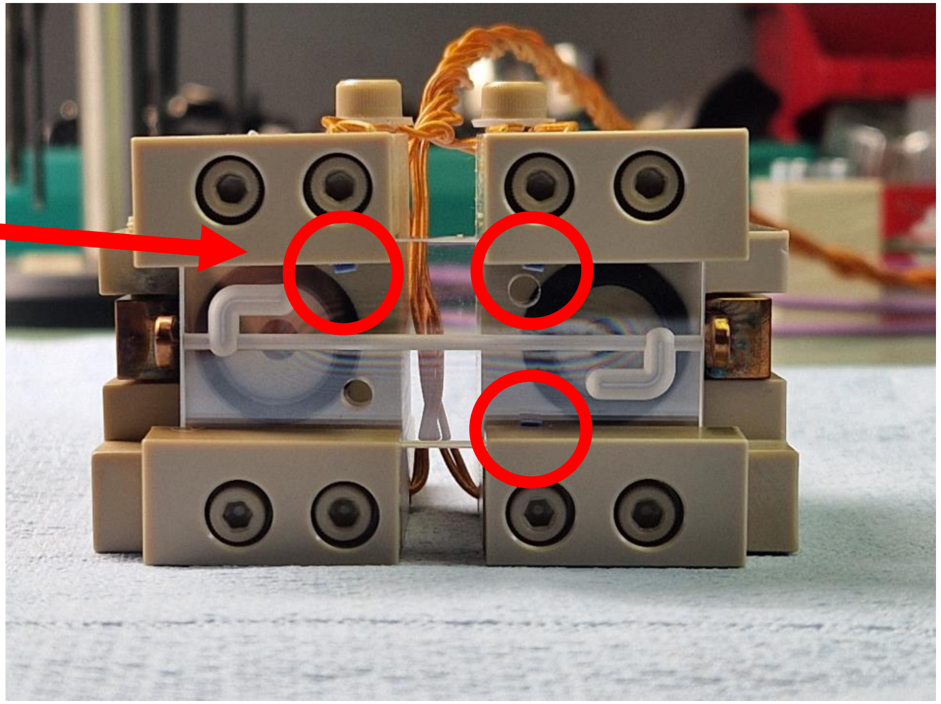

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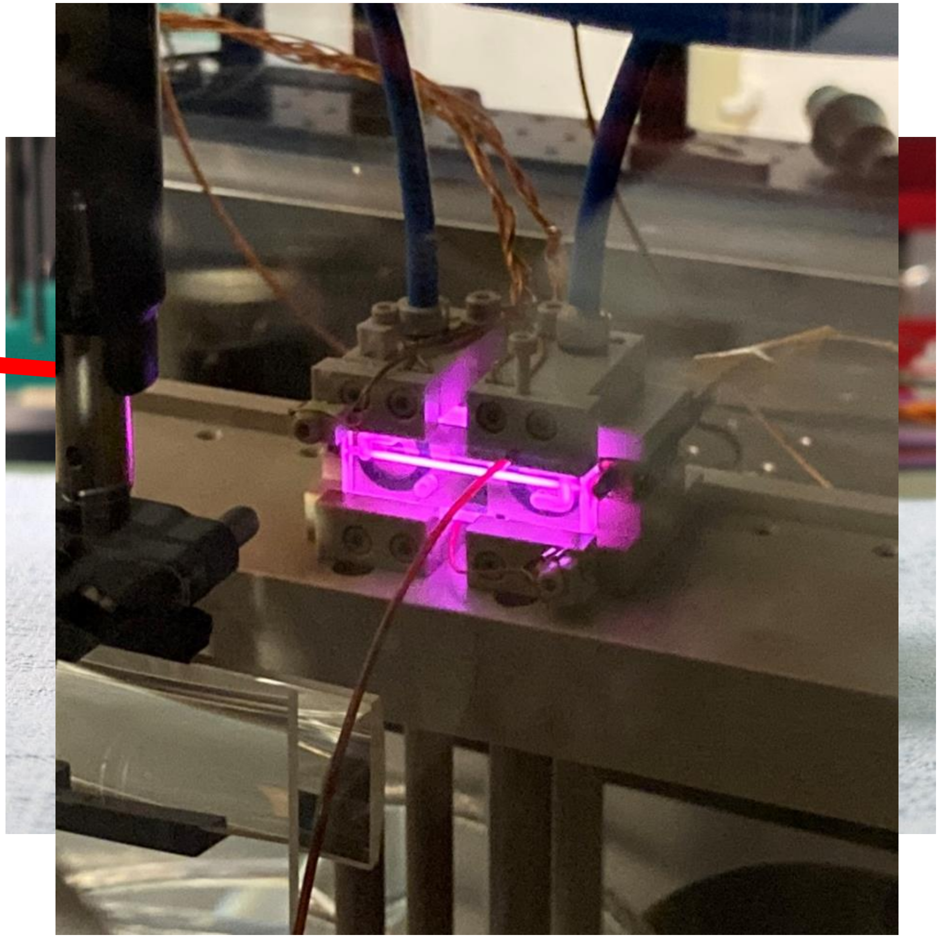

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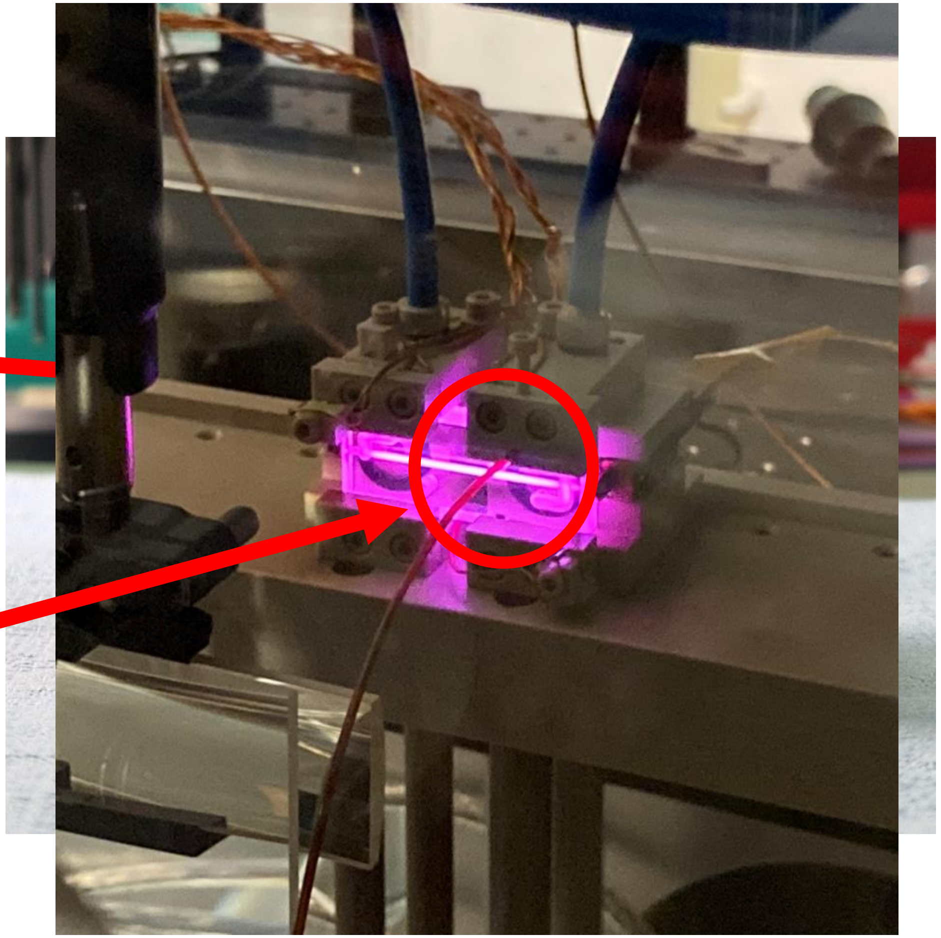
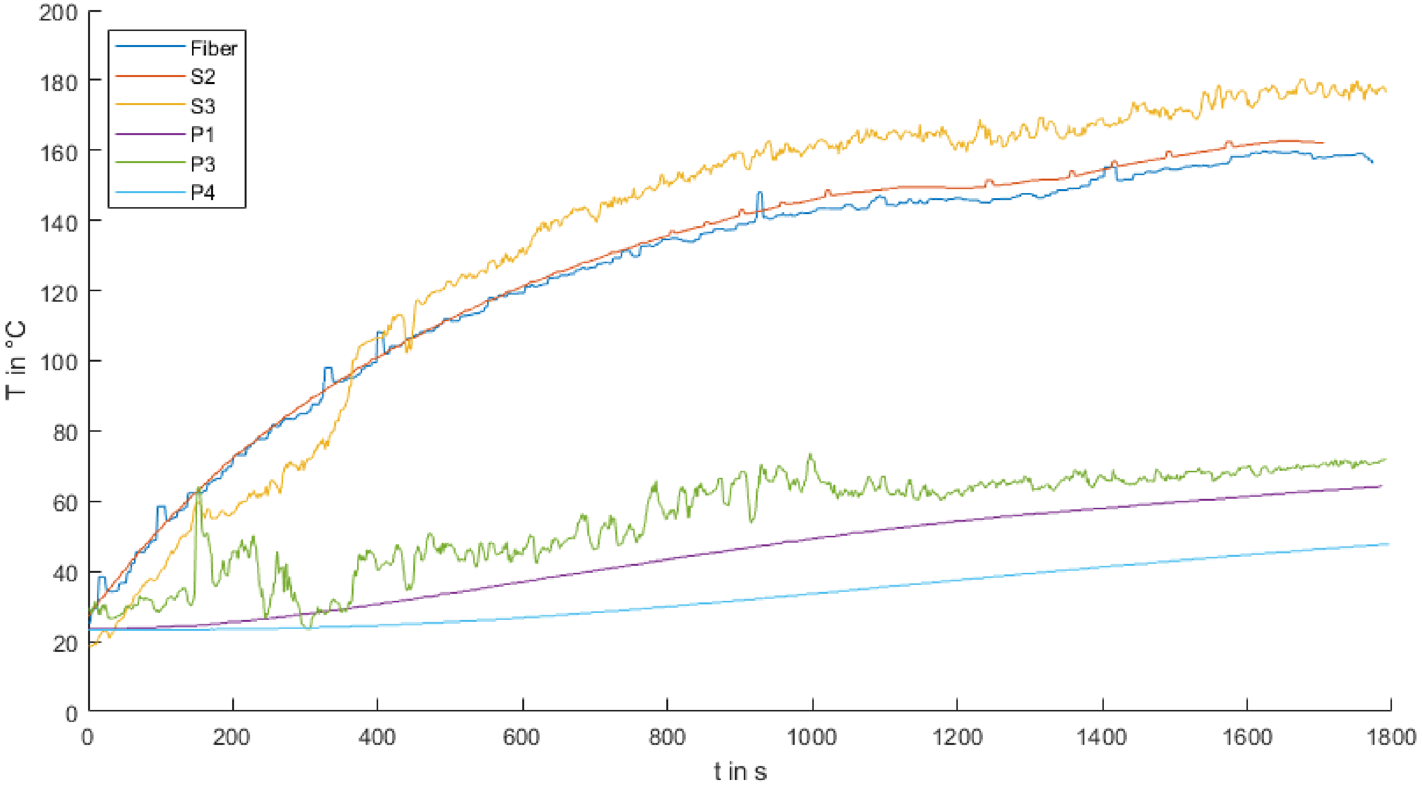


Temperature Measurements

Cell Temperature Studies

- PT1000 allows to measure at different parts of the cell
- But Fiber optic system seems much more reliable and safer to operate

H2, rep rate 200Hz



Temperature Measurements

Comparison to simulations

- Preliminary simulation results show good agreement with experiments, but simulations still need more work:
    - Assumptions: Perfect heat transfer between components. 1kHz rep. rate with 20kV energy deposition of 3.6 J/m per discharge
    - This experiments give us some insight into the scaling of the power deposition into the cell, which will allow us to extrapolate into much higher repetition rates.

Summary and Outlook

- TCI promises to be a good diagnostic for temporal and spatially resolved density for MHz pulses.
- Having radial profiles would help us to benchmark previous measurements.
- Temperature measurements help us prepare on what to expect at MHz rep rates and to think about effective cooling solutions
- Next steps:
    - Setup of the TCI diagnostic in the ADVANCE lab using MHz pulser and TiSa Laser system.
    - Look at other types of diagnostics for longitudinally resolved density.

Thank you

Specific case: Plasma capillary

Gaussian Laser: 788nm, 35 fs, ~2.7W averaged power

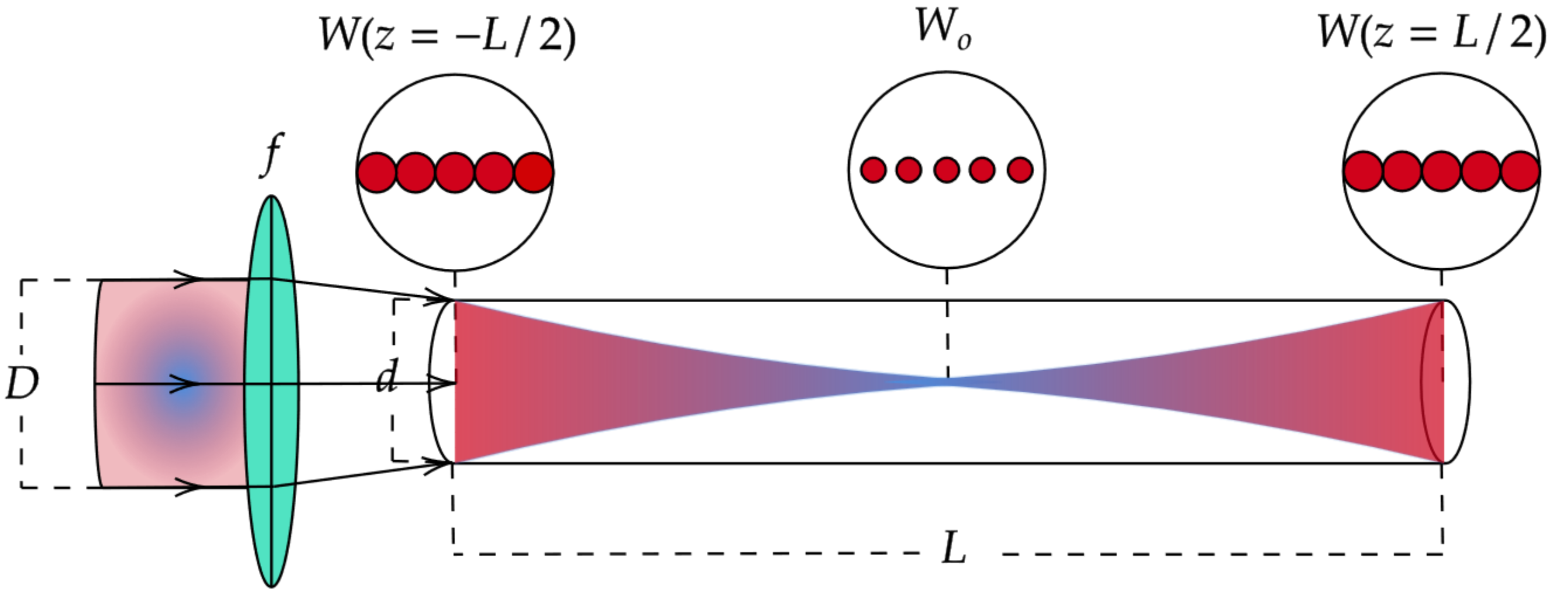
- $W(z) = W_0\sqrt{1+\left(\frac{z}{Z_R}\right)^2}$

- $W_0 = \frac{2\lambda}{\pi}\frac{f}{D} = \frac{2\lambda}{\pi}F_\#$ $\qquad \frac{f}{D} = F_\#$

- $W_0' = W_0 M^2 = \frac{2\lambda}{\pi}M^2 F_\#$

- $Z_R = \frac{\pi}{\lambda}W_0^2 = \frac{4\lambda}{\pi}\left(\frac{f}{D}\right)^2$

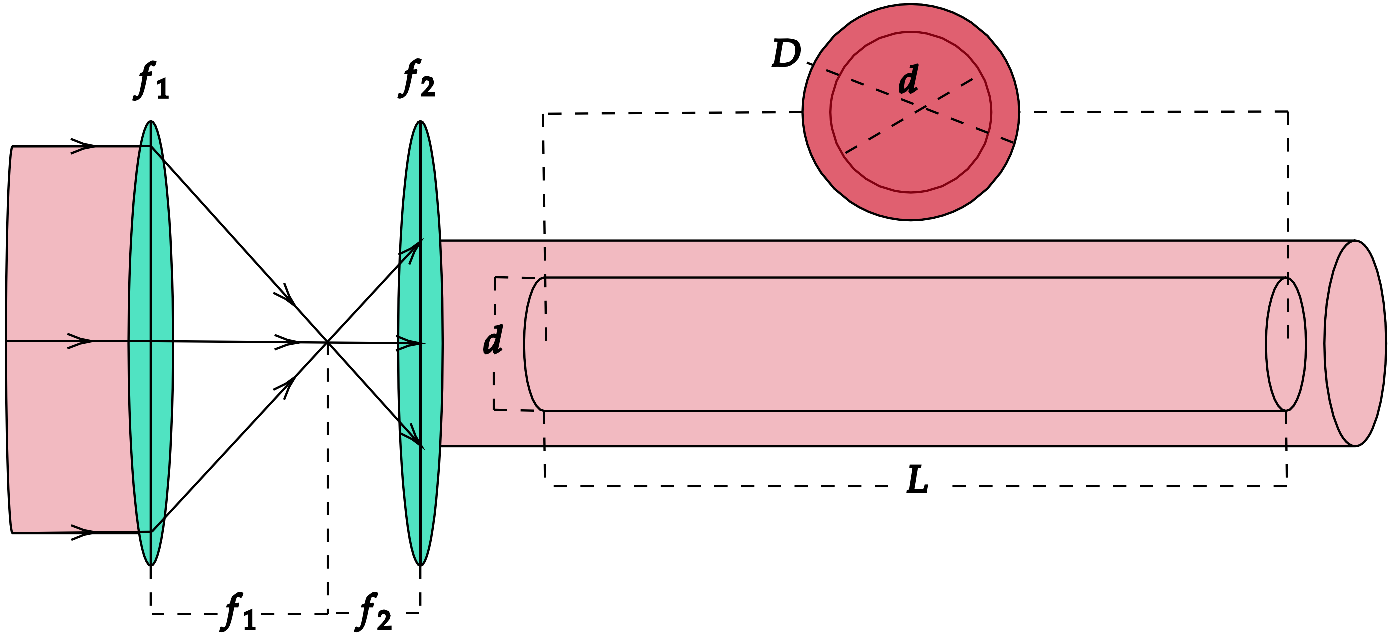
- $Z_R' = \frac{Z_R}{M^2} = \frac{4\lambda}{\pi}\left(\frac{f}{D}\right)^2\frac{1}{M^2} = \frac{4\lambda}{\pi M^2}F_\#^2$



Two color laser interferometry

Collimated Laser beam

- Spectrometer can resolve the fringes spatially.
- Beam around the same size of the capillary diameter ~1.5 mm
- Laser diameter is ~8 mm. Sizing down the beam without reaching 10^12 W/cm^2
- Possibility to damage to the BBO crystals.



Backups

Explain two different flavours of TCI

Time offset

- $\Delta t = t(\omega, L) - t(2\omega, L)$

1. $t(\omega, L) = \frac{L}{V_{group}} = \frac{L}{c}\left(1 - \frac{\omega_p^2}{\omega^2}\right)^{-\frac{1}{2}} \approx \frac{L}{c}\left(1 + \frac{\omega_p^2}{2\omega^2}\right)$
2. $t(2\omega, L) = \frac{L}{V_{group}} = \frac{L}{c}\left(1 - \frac{\omega_p^2}{(2\omega)^2}\right)^{-\frac{1}{2}} \approx \frac{L}{c}\left(1 + \frac{\omega_p^2}{8\omega^2}\right)$

- $\Delta t \approx \frac{L}{c}\left(\frac{3\omega_p^2}{8\omega^2}\right)$

$$\eta = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

$$V_{group} = c\eta$$

$$V_{phase} = \frac{c}{\eta}$$

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

Phase difference

- $\Delta\phi = \omega \frac{L}{V_{phase}} - \omega \frac{L}{V_{phase}}$
- $\Delta\phi == \frac{\omega}{c}\eta(\omega)L - \frac{\omega}{c}\eta(2\omega)L$
- $\Delta\phi \approx \frac{\omega L}{c}\left[\left(1 - \frac{\omega_p^2}{2\omega^2}\right) - \left(1 - \frac{\omega_p^2}{8\omega^2}\right)\right]$
- $\Delta\phi \approx \frac{\omega L}{c}\left[-\frac{3}{8}\frac{\omega_p^2}{\omega^2}\right] = -\omega\Delta t$

But this is the phase shift in terms of red – we frequency double to blue, therefore the measured absolute shift:

$$\Delta\phi = \frac{3\omega_p^2 L}{4c\omega}$$

$$\mathrm{n_e} = \frac{4\epsilon_0 m_e c}{3e^2}\frac{\omega}{L}\Delta\phi$$

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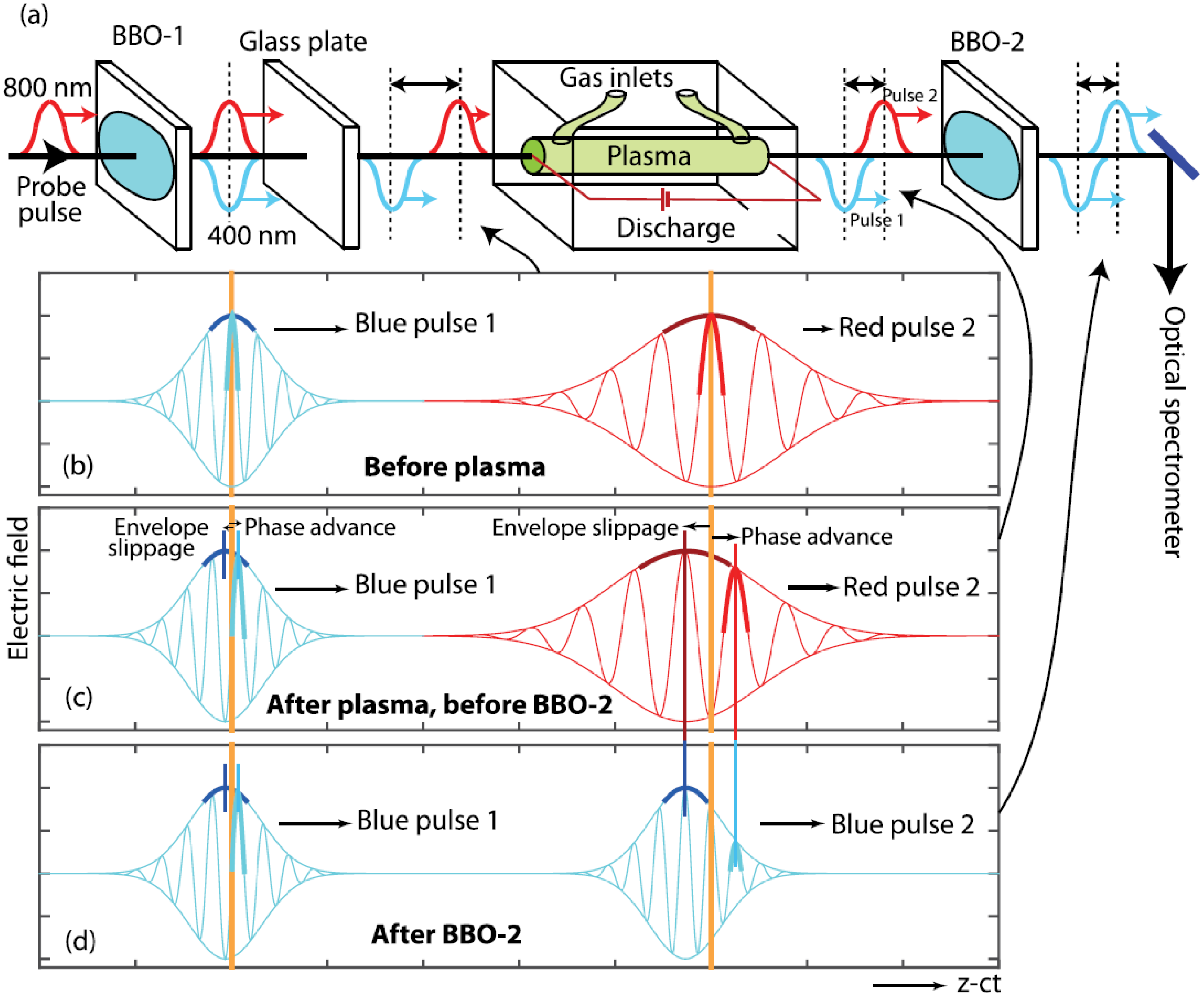

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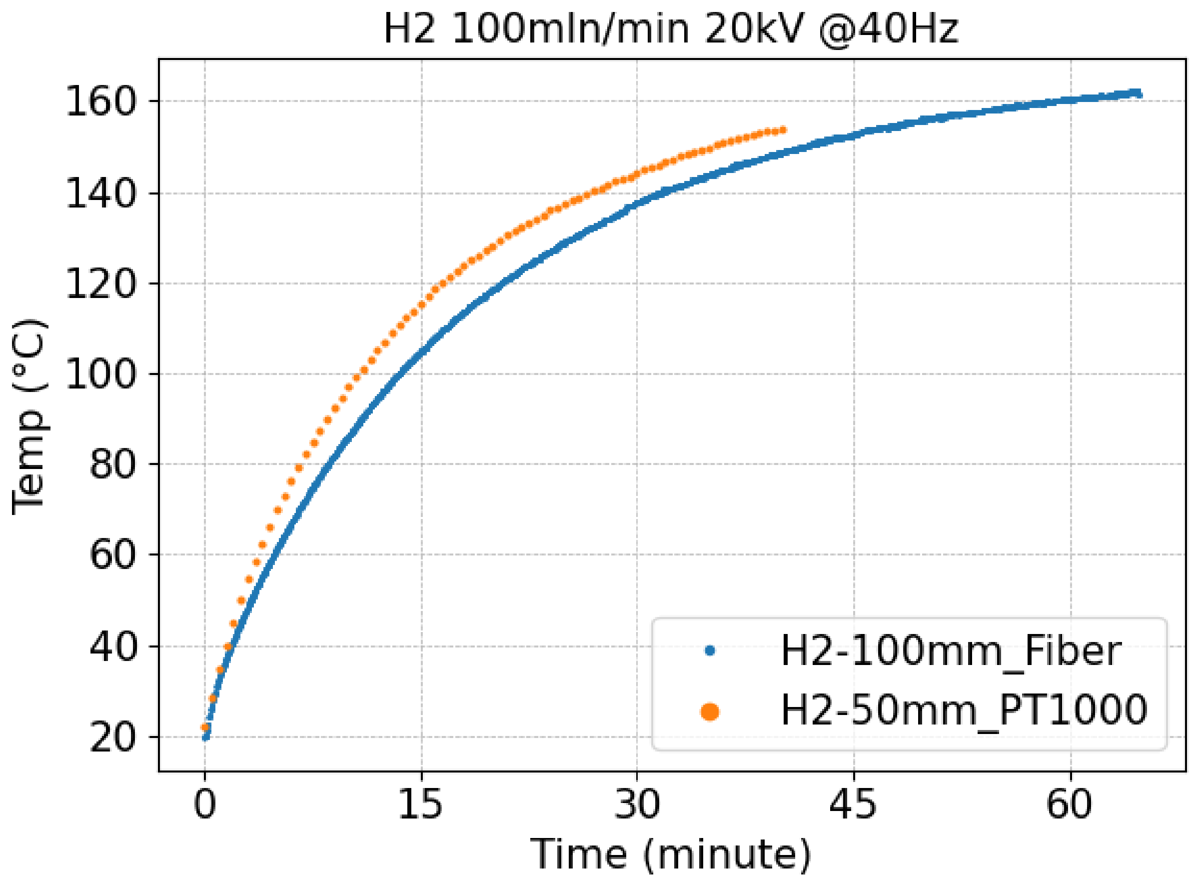
H2 100mln/min 20kV @40Hz
160
140
120
100
80
60
40
20
Temp (°C)
0
15
30
45
60
Time (minute)
H2-100mm_Fiber
H2-50mm_PT1000

Two color laser interferometry

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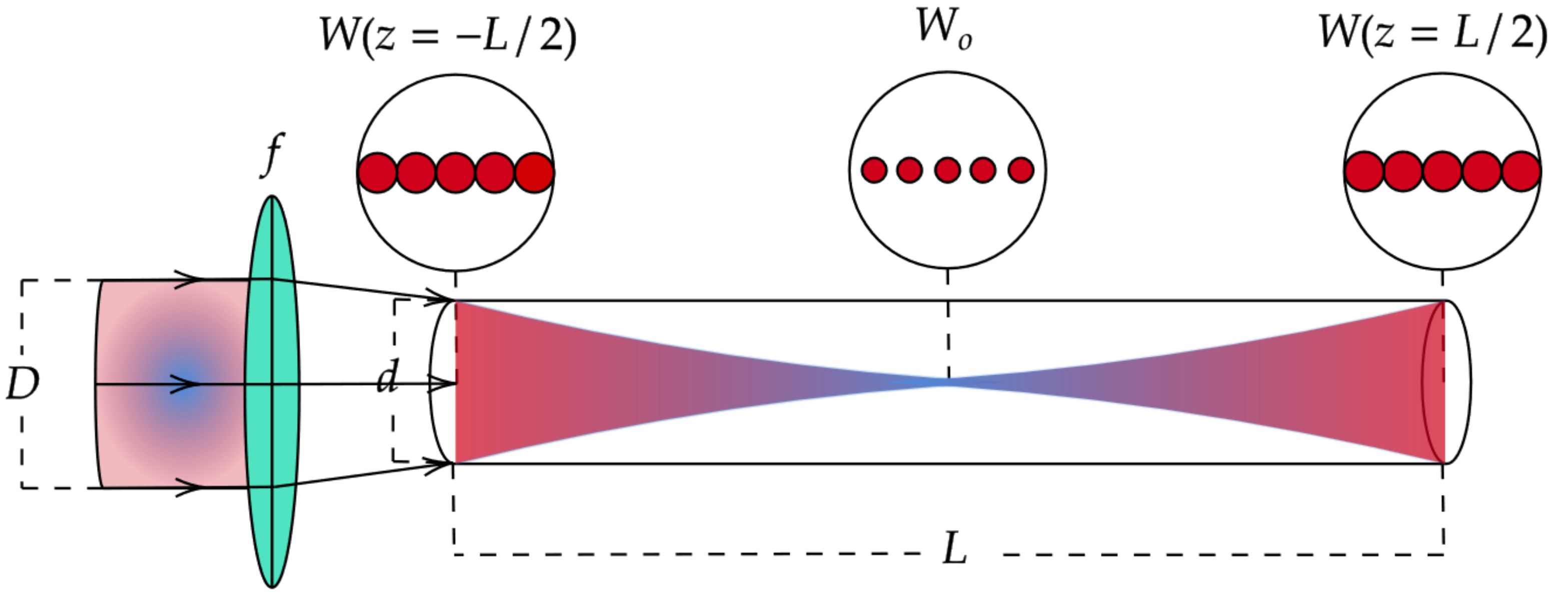


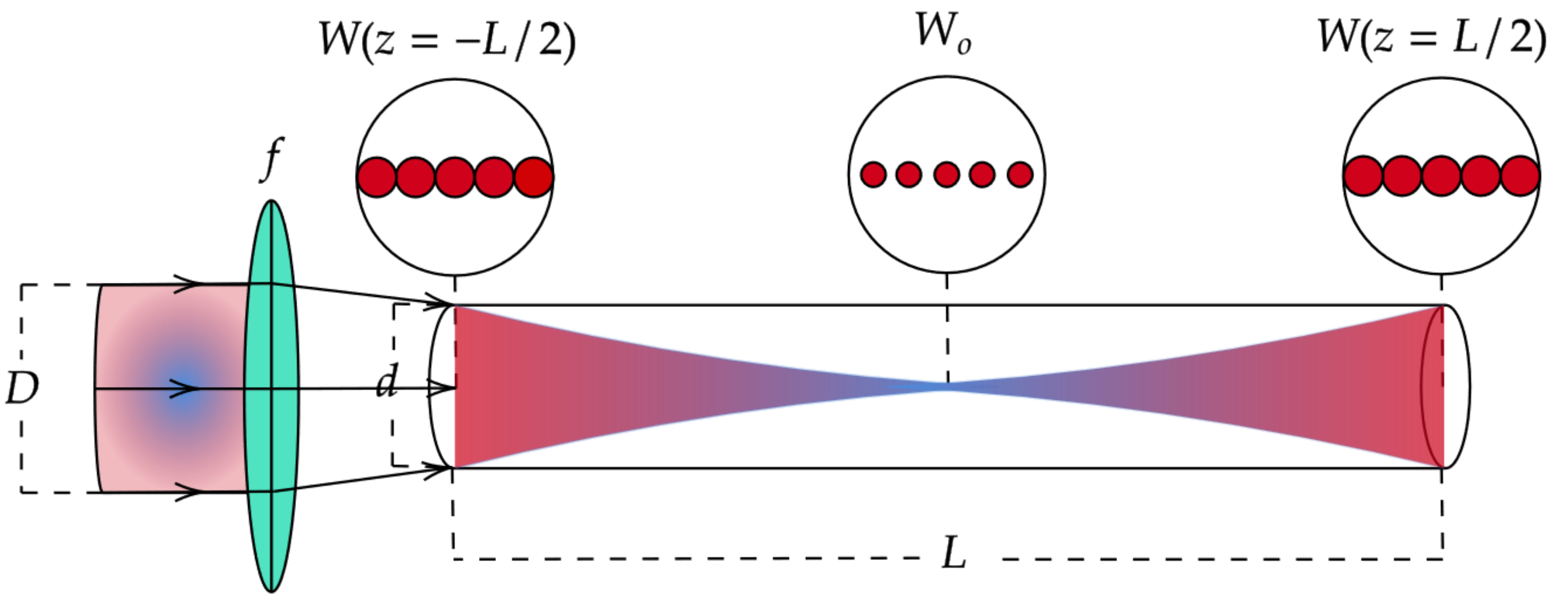
Specific case: Plasma capillary

- $W\left(z=\pm\frac{L}{2}\right)=W_0'\sqrt{1+\left(\frac{L}{2Z_R'}\right)^2}$

- $W(\frac{L}{2})=\frac{2\lambda}{\pi}M^2F_\#\sqrt{1+\frac{L^2\pi^2(M^2)^2}{64\lambda^2F_\#^4}}$

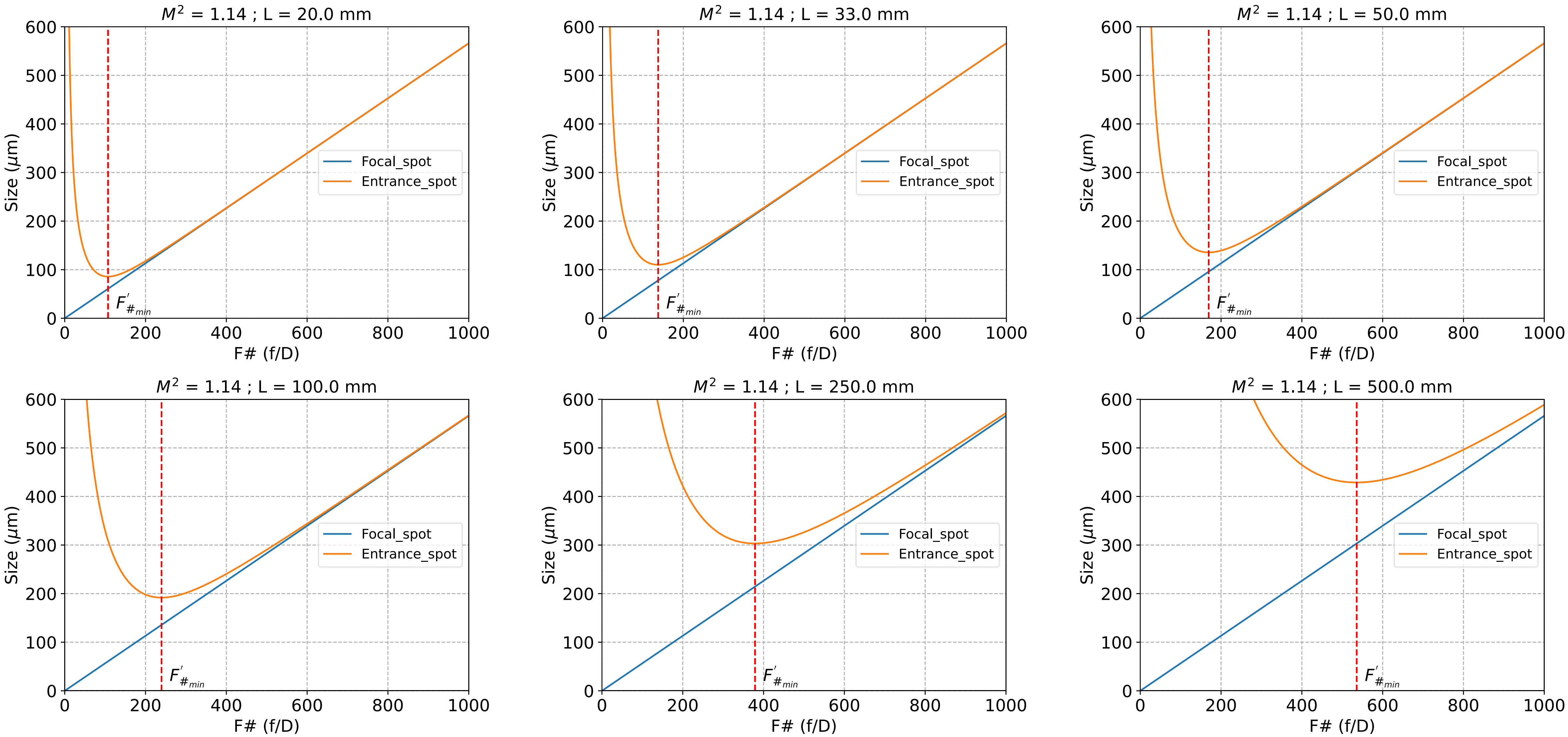
- $\frac{\partial W_{\frac{L}{2}}}{\partial F_\#}|_{min}=0$

- $F_{\#_{min}}=\frac{1}{2}\sqrt{\frac{L\pi M^2}{2\lambda}}$



Specific case: Plasma capillary

Comparison between different capillary lengths



Specific case: Plasma capillary

Comparison between different capillary lengths

Cell Length (mm)	Diameter (mm)	$F'_{\#min}$	W'_0 (μm)	$W'(L/2)$ (μm)	# of spots
20	1.5	107	60.65	85.77	8
33	1.5	138	77.91	110.18	6
50	1.5	169	95.90	135.62	5
100	1.5	240	135.62	191.79	3
250	1.5	379	214.43	303.25	2
500	1.5	536	303.25	428.86	1

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