Hybrid LWFA-driven PWFA as a test platform for staged plasma acceleration

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Hybrid Collaboration partners:

General concept of Hybrid LWFA-PWFA staging

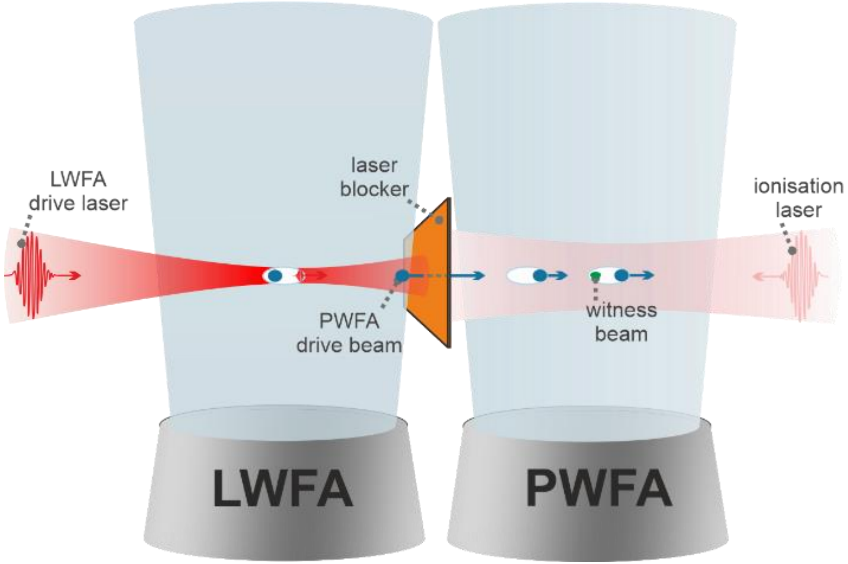
Combine complementary features of **LWFA** (e.g. high peak current, compact) and **PWFA** (e.g. dephasing free, cold injection schemes) via staging:

by **driving PWFA** with **LWFA beam** with the **potential** to reach:

→ **Higher brightness**

→ **Enhanced stability**

→ **Higher energy**



Theory and Concept:

Hidding, B. et al: **PRL 104**, 195002 (2010)

Martinez de la Ossa, A. et al. **Phil. Trans. R. Soc. A 377**: 20180175 (2019)

Hidding, B. et al: **Appl. Sci. 2019**, 9, 2626 (2019)

Experimental Realizations:

Gilljohann, M. et al. **PRX** 9, 011046 (2019)

Kurz, T. et al. **Nat Commun 12**, 2895 (2021)

Couperus Cadabag, J. et al**. Physical Review Research 3**, L042005 (2021)

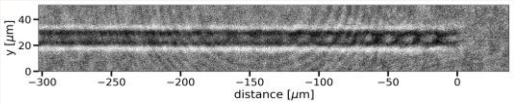
Foerster, M. et al. **PRX 12**, 041016 (2022)

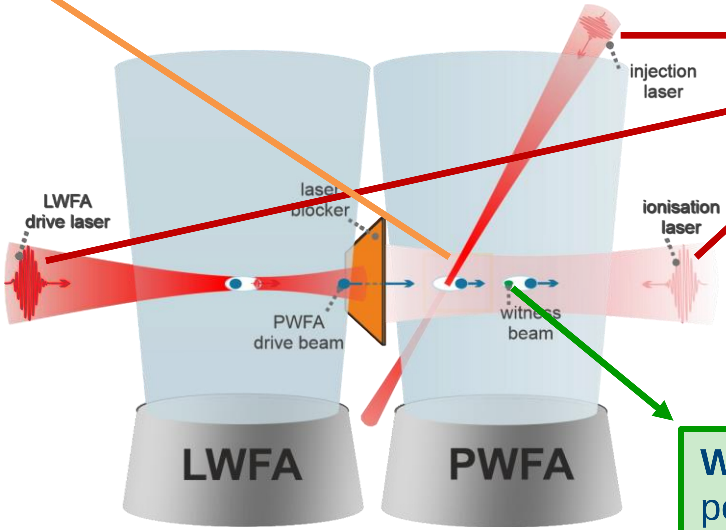
Schöbel, S. et al. **New J. Phys. 24** 083034 (2022)

How can Hybrid LWFA-PWFA help address staging questions?

Open geometry: accessible for **in situ, non-invasive** diagnostics as **probing** with **high spatial** and **temporal resolution**:

- precise **tracking** of laser and electron beams by their filaments
- in situ **density measurements**





Temporal and spatial coupling of **different electron** and **laser beams** used for driver generation, witness injection and pre-ionization

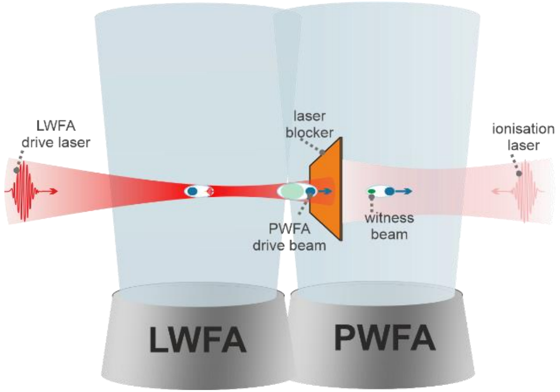
Witness beam could potentially have:

- **higher quality** (brightness)
- **improved stability**

First results of Hybrid LWFA-PWFA staging via external injection

First steps @ HZDR and LMU:

- **Observation** of **beam driven plasma waves**: LWFA beam is capable to drive a wake in a subsequent stage
- **Acceleration** of **witness beams** via recapturing downramp (HZDR) or second bucket injection (LMU) from LWFA
- **Different acceleration gradients** in **pre- vs. self-ionized** regime



Kurz, T. et al. Nat Commun 12, 2895 (2021)

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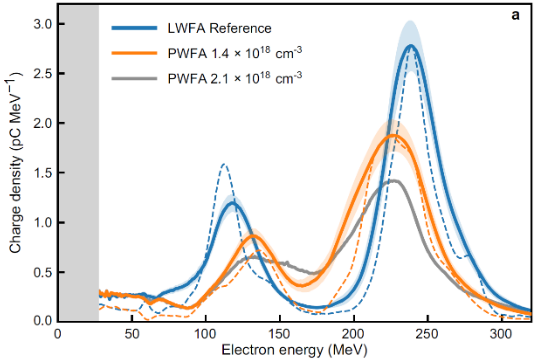
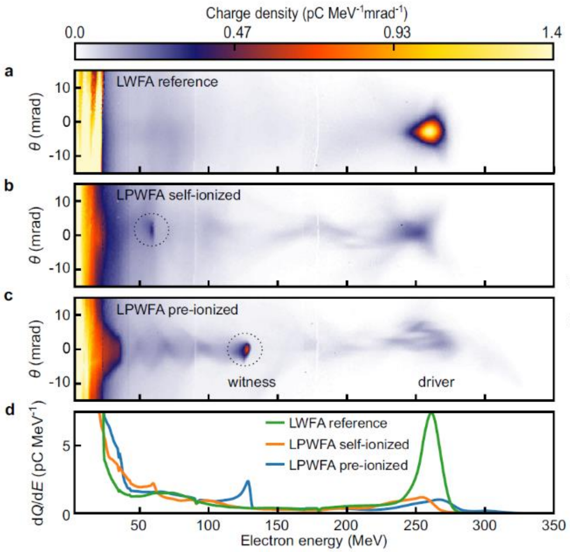
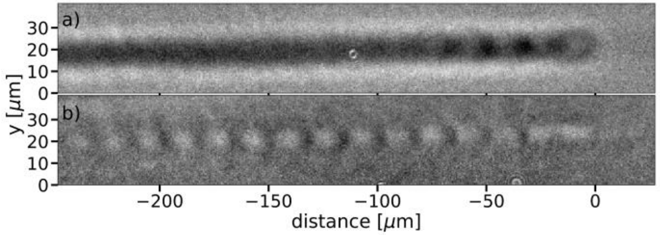




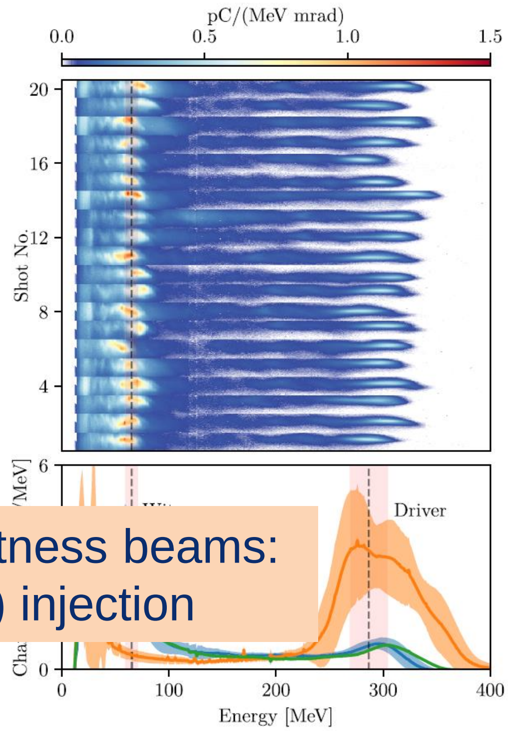


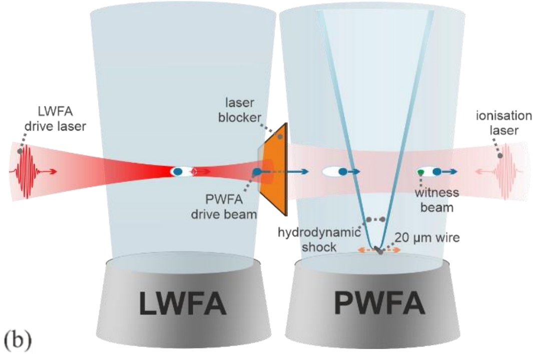
Internal injection via injection at a density downramp

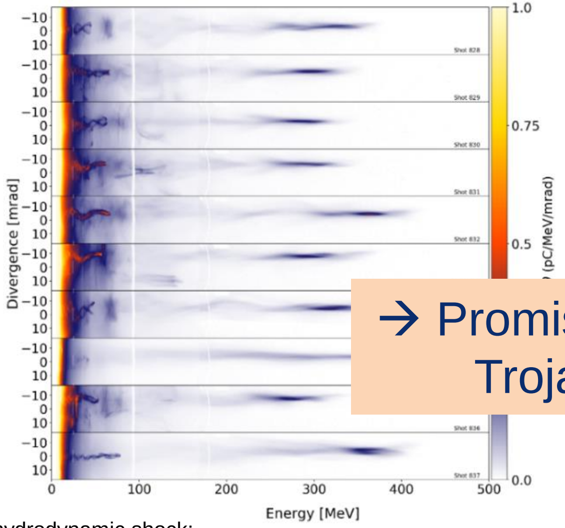
Controllable injection at a density downramp

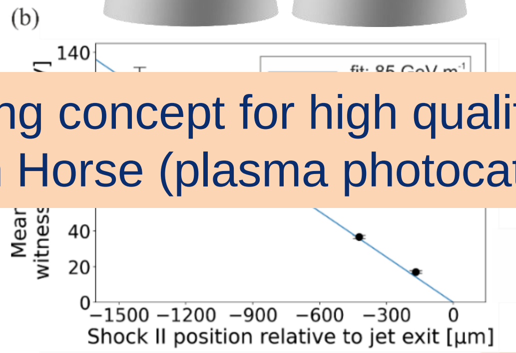
- **reliable injection** from **hydrodynamic** or **optically** generated **shock**
- witness energy controllable via shock position
- no high witness energy
- no good witness quality

Optically generated shock:
Foerster, M. et al. **PRX 12**, 041016 (2022)









→ Promising concept for high quality witness beams: Trojan Horse (plasma photocatode) injection

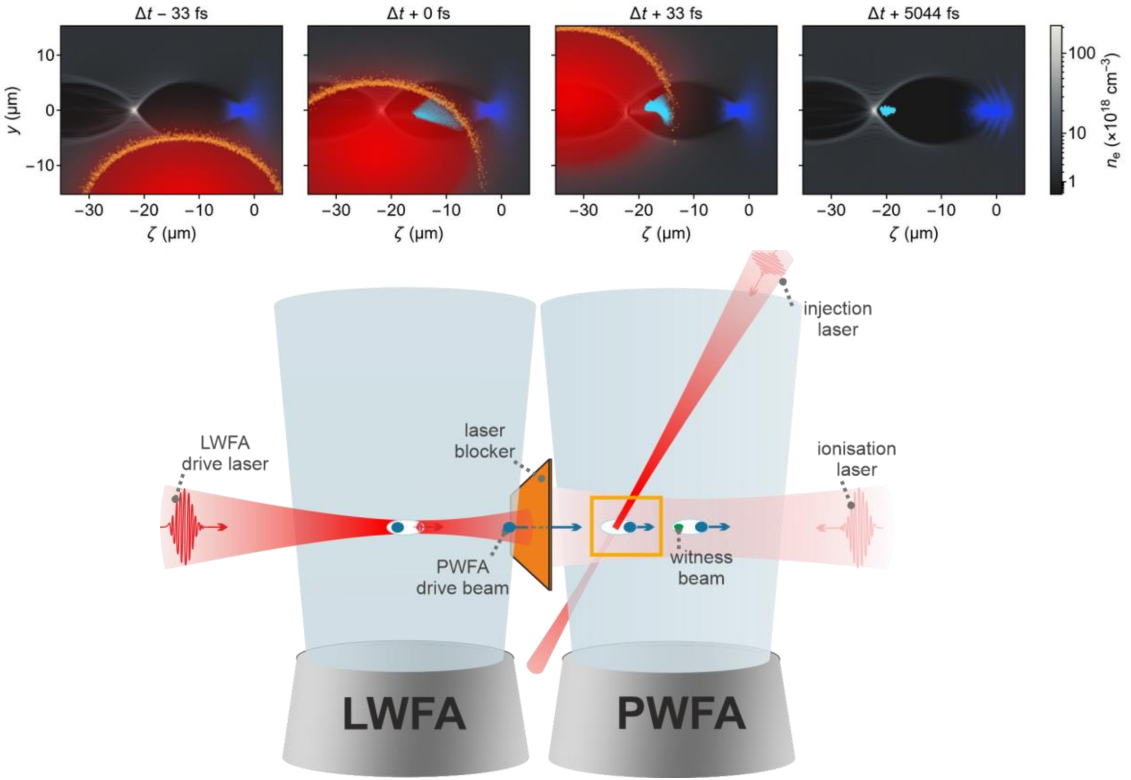
hydrodynamic shock:
Couperus Cabadağ, J. P. et al. **Phys. Rev. Research** 3 (2021)

Concept of Trojan Horse injection

Idea:

use **ionization** (in this case: 2nd level of Helium) to **release** the **witness electrons** directly **inside the cavity**

- Ionization done by an **additional injector laser**
- Requires precise **spatial temporal overlap** of **injection laser (⌀ 16µm)** and **1st cavity (here: 25-30µm length)**
- **Monitored** using **few-cycle probe** beam

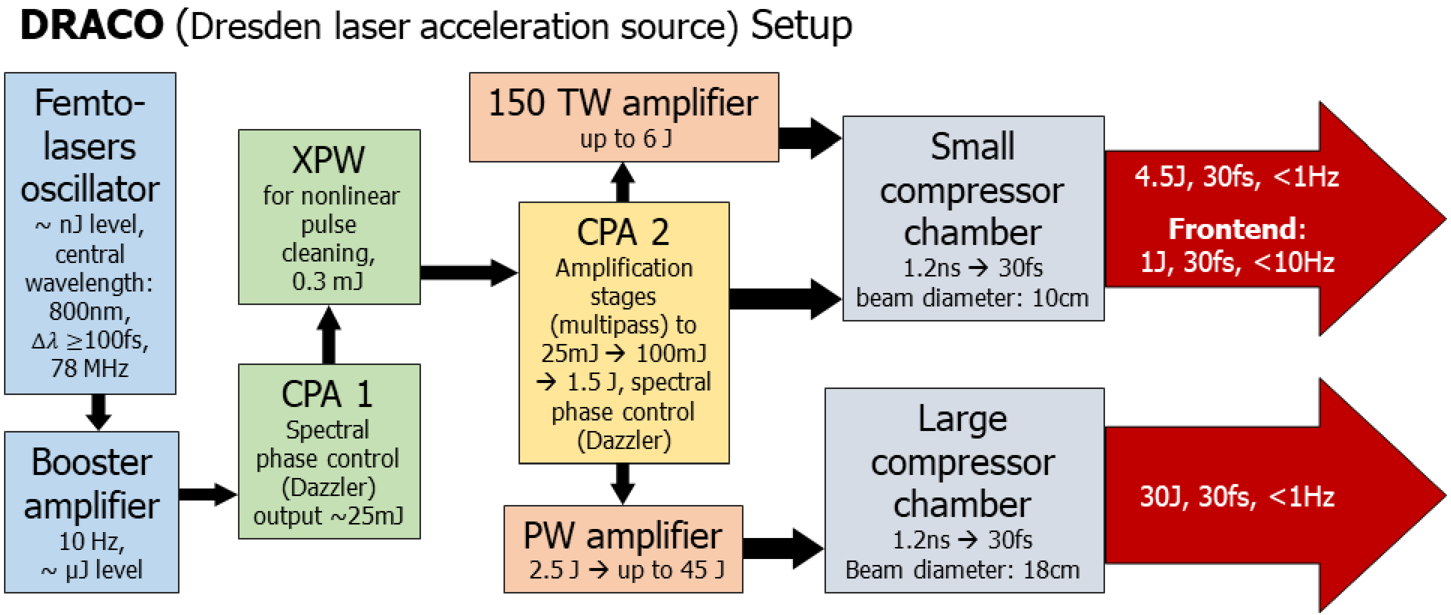


→ **Need of four laser beams** in total:
LWFA driver, Injector laser, source for few-cycle probe beam, pre-ionization laser for PWFA stage

Experimental realization of Trojan Horse injection @DRACO

Need of **four laser beams**:
LWFA driver, Injector laser, source for few-cycle probe beam, pre-ionization laser for PWFA stage

→ **All beams** are **extracted** from the **two arms** of the **DRACO laser system**
(~ 80m from splitting point to target)



150TW arm

→ LWFA driver beam

→ few cycle probe

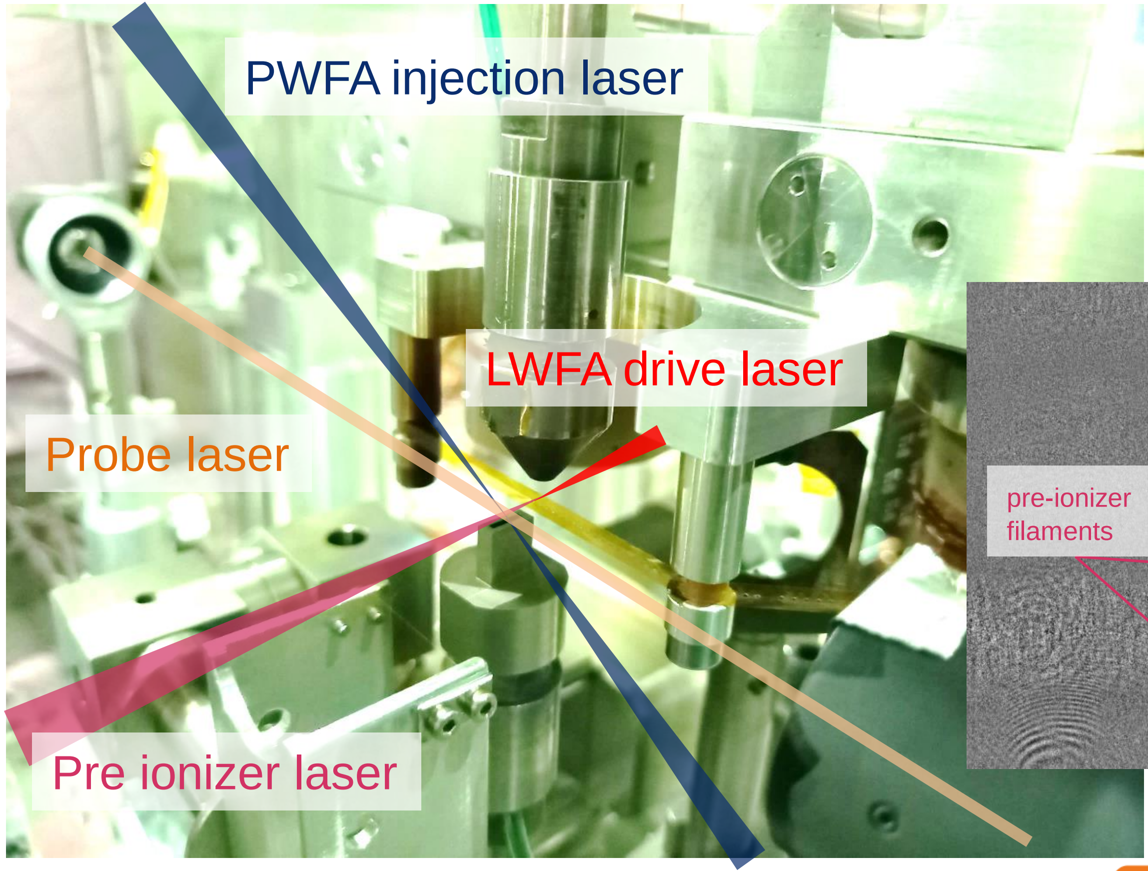
1 PW arm

(not fully amplified, only a part of the beam)

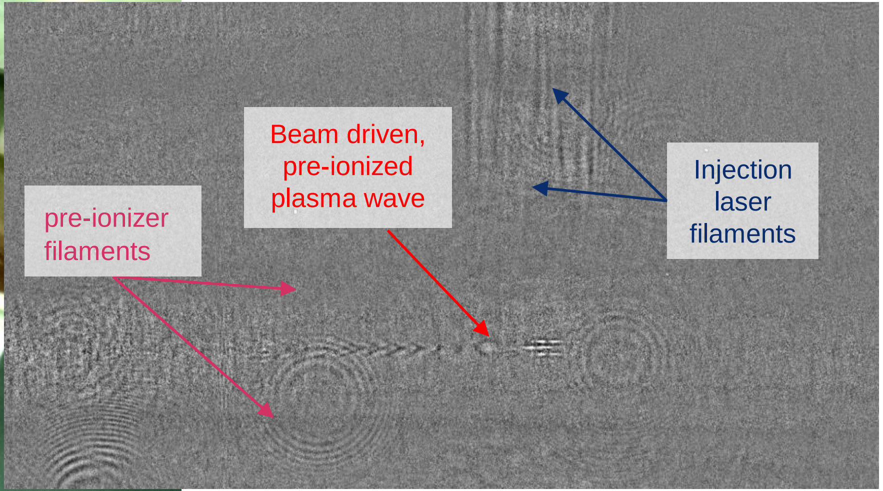
→ Injection laser

→ Pre-ionization laser

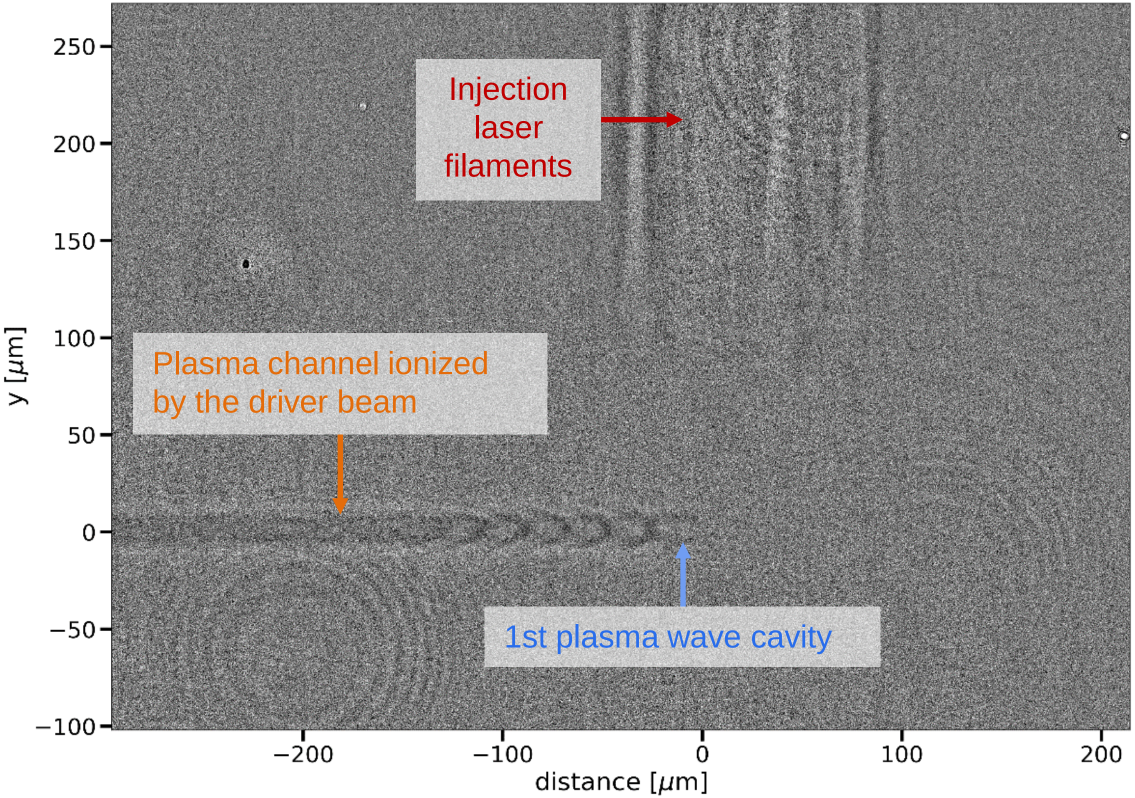
Experimental realization of Trojan Horse injection @DRACO



Traces of all beams in the PWFA stage visible on the shadowgraphy image:



Spatial-temporal overlap using shadowgraphy

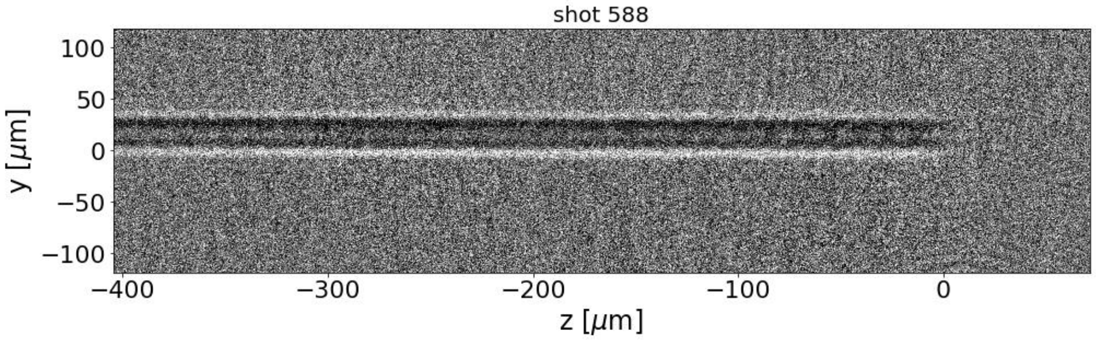


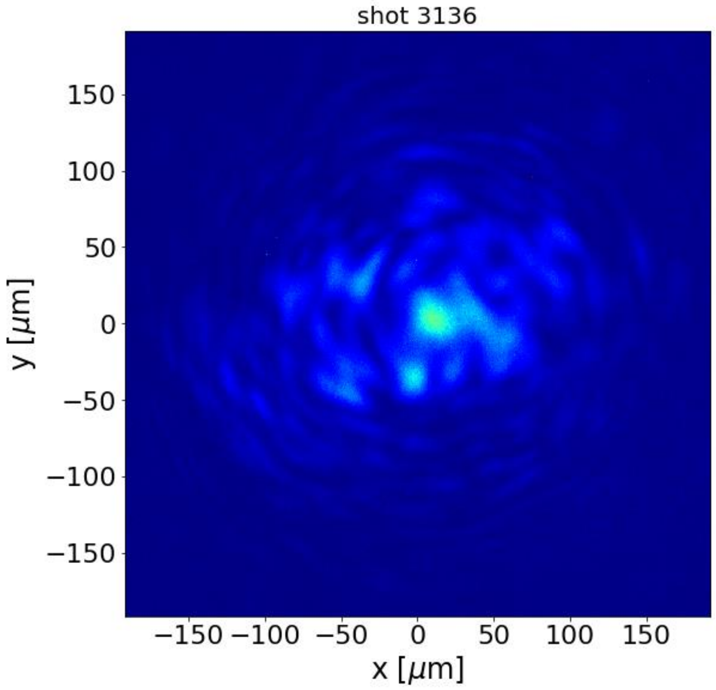
- **Adjustment of:**
  - Arrival time
  - location of the interaction point
- **in situ monitoring** of jitters/drifts
- Shadowgraphy is only a **projection**:
  - need of **additional cameras** to monitor the pointing
  - Potential solution: probing from two different angles

Shot to shot jitters

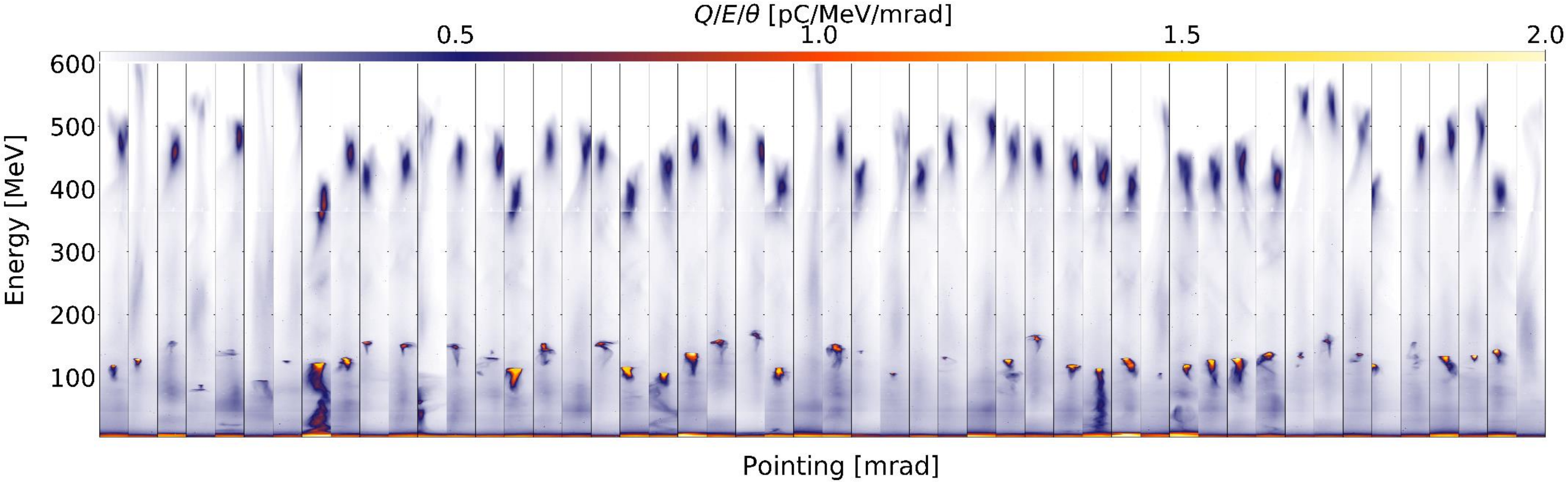
Shot-to-shot jitter and **drift** can be **monitored** using online in situ diagnostics (**shadowgraphy**, **camera** monitoring the injector laser **after interaction**)

For stable witness injection via Trojan Horse injection: **small shot-to-shot jitter required** to overlap injector laser and first cavity **reliably**





High witness injection probability shows reliable overlap

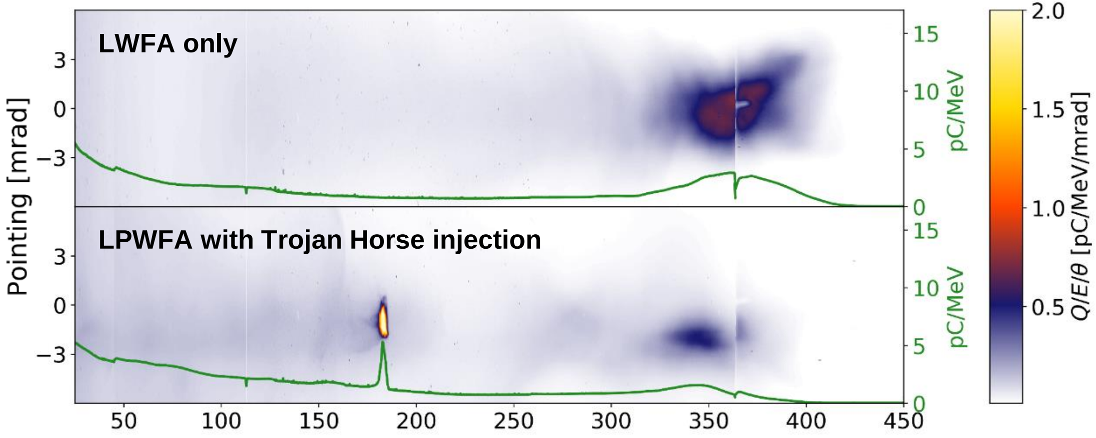


50 consecutive shots with unchanged nominal parameter (45 successful shots, one with no laser blocker)
→ ~92% injection rate

- → sufficient stability of injection laser through plasma
- → sufficient stability of the electron driver beam
- → Witness beam parameter still jitter due to jitter of overlap and driver beam parameters

PWFA stage towards quality booster

- **Witness beam parameters not stable** yet, potential sources:
  - Alignment of 1st cavity and injection laser jitters
  - **He+ partially ionized by the driver beam**
    → available charge jitters with drive beam parameter
- some shots show **promising parameters**, especially low energy spread
- Comparison of peak height in the lineout:
  reference shot: 2.96 pC/MeV
  average ref. shots: 1.84 pC/MeV
  witness beam: 4.16 pC/MeV
  → higher than best reference shot



Witness beam parameters:

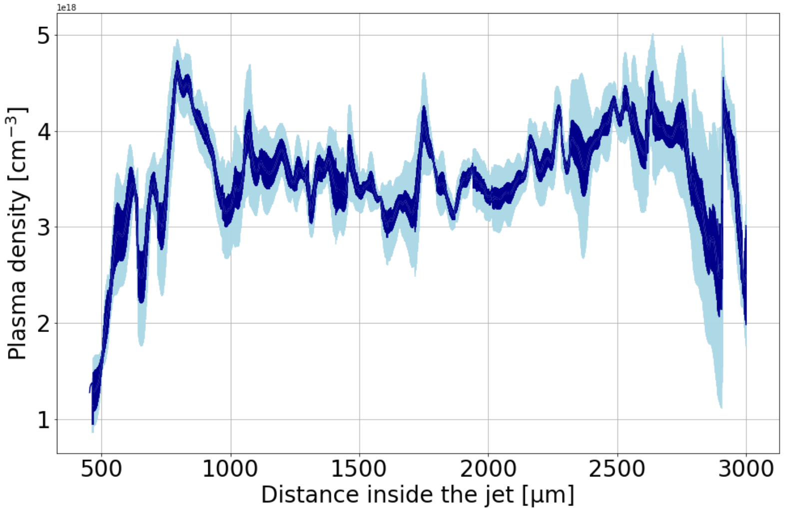
mean energy:
183 MeV

charge (FWHM):
8.7 pC

energy spread:
2.7 MeV (1.5%)

divergence (rms):
0.59 mrad

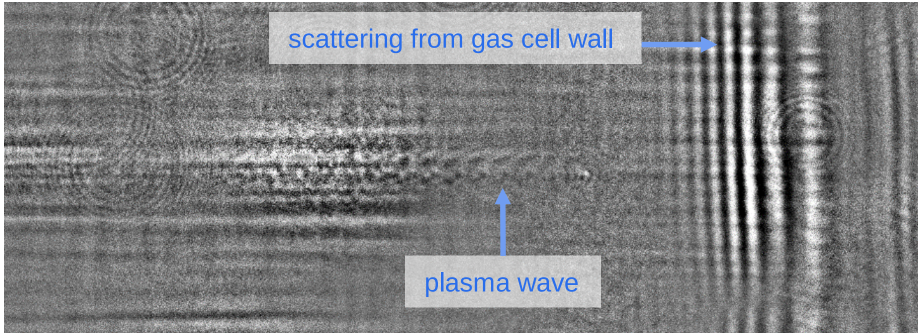
Plasma density measurements using shadowgraphy



Density measurements using probing:

- plasma wavelength provides **local density measurement** using shadowgraphy (demonstrated to work for at least $\mathbf{1.7 \cdot 10^{17}}$**cm^{-3} to** $\mathbf{1 \cdot 10^{19}}$**cm^{-3}**)
- **scan through the target**: **high resolution** density measurement of **plasma profile** along the interaction channel
  → can **detect irregularities** along the profile
- **online measurement** of the overall density possible

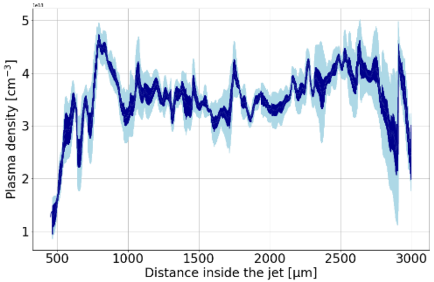
collaboration experiment with groups of Brigitte Cros and Sandrine Dobosz : **density measurement** using plasma wave probing works in a **gas cell** (3.6mm thick fused silica walls)

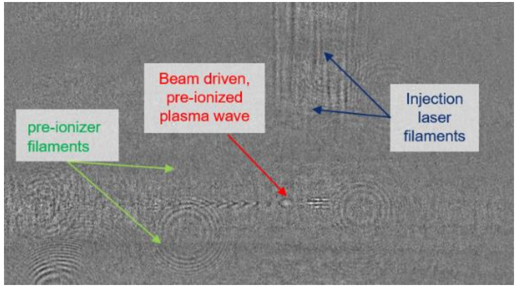


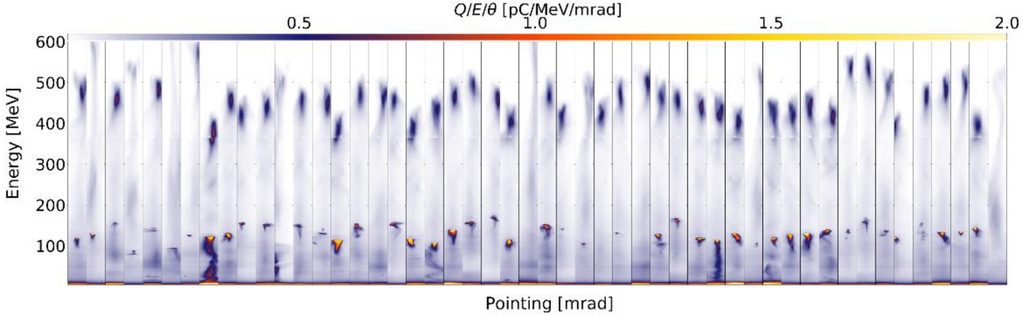
TNA Proposal ID: 24579 (2023)

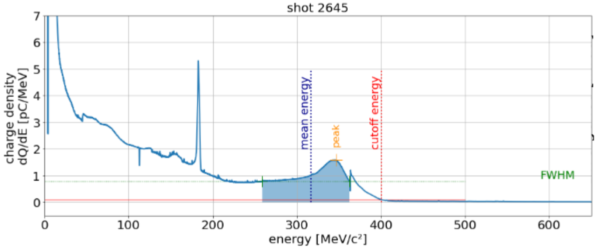
Summary

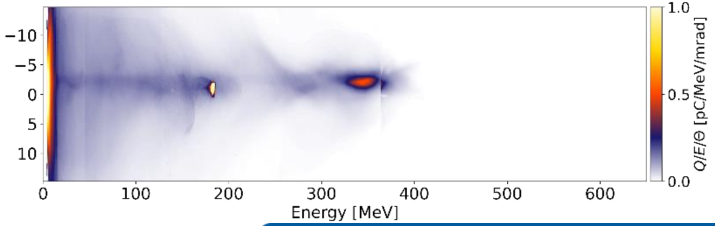
- **Probing** is the **key diagnostic** to check **alignment** and **timing** as **required** for **staging**
  - tracking of **drifts,** estimate **shot-to-shot jitter**
  - local **plasma density** measurements
  - probing also works in **gas-cell**
  - future: tomographic probing?
- **Trojan horse demonstrated**
  - Demonstrates **ability** to get **reliable spatio-temporal overlap** of injection laser and 1st cavity
  - **Quality booster**











Thank you for your attention!

And thanks to all the involved people:

Hybrid collaboration partners:

Alberto Martinez de la Ossa
Sebastian Corde
Stefan Karsch
Bernard Hidding
Alastair Nutter
Thomas Heinemann
Olena Kononenko
Andreas Döpp
Max Gilljohann
Moritz Förster

HZDR:

Arie Irman
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Vincent Chang
Amin Ghaith
Maxwell LaBerge
Susanne Schöbel
Franziska Herrmann
Patrick Ufer
Richard Pausch
Alexander Debus
Klaus Steiniger

Université Paris Saclay and CEA:

Brigitte Cros
Sandrine Dobosz
Francesco Massimo
Abhishek Panchal
Charles Ballage
Ovidiu Vasilovici
Lodewyk Steyn

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Density limits of the probing:

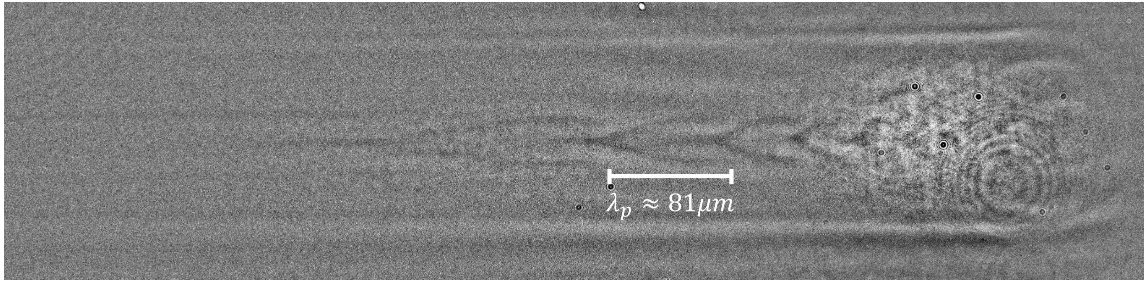
Limits of the density analysis using shadowgraphy and few-cycle probing:

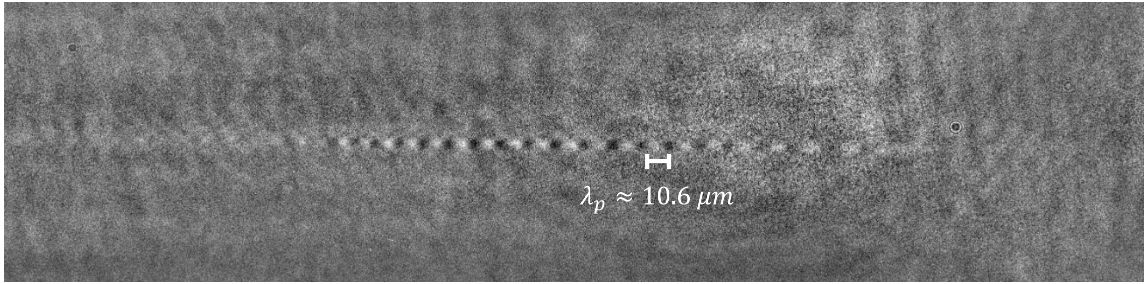
Visible cavities at least between:

81µm length ≙ $1.7 \cdot 10^{17}$cm^{-3}

and

10.6µm length ≙ $9.9 \cdot 10^{18}$cm^{-3}





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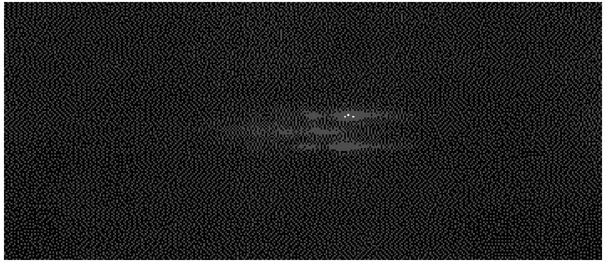
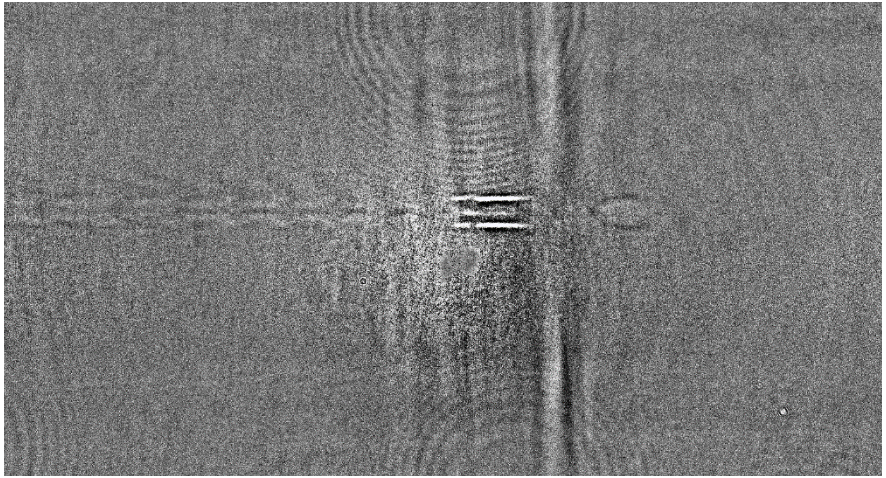


Light signal

- Emitted light when injector laser hits a plasma sheath
- Used for alignment in the axis which is unaccessable for the probe
- Appears directly in line with the plasma wave at the interaction point: only there if there is an overlap



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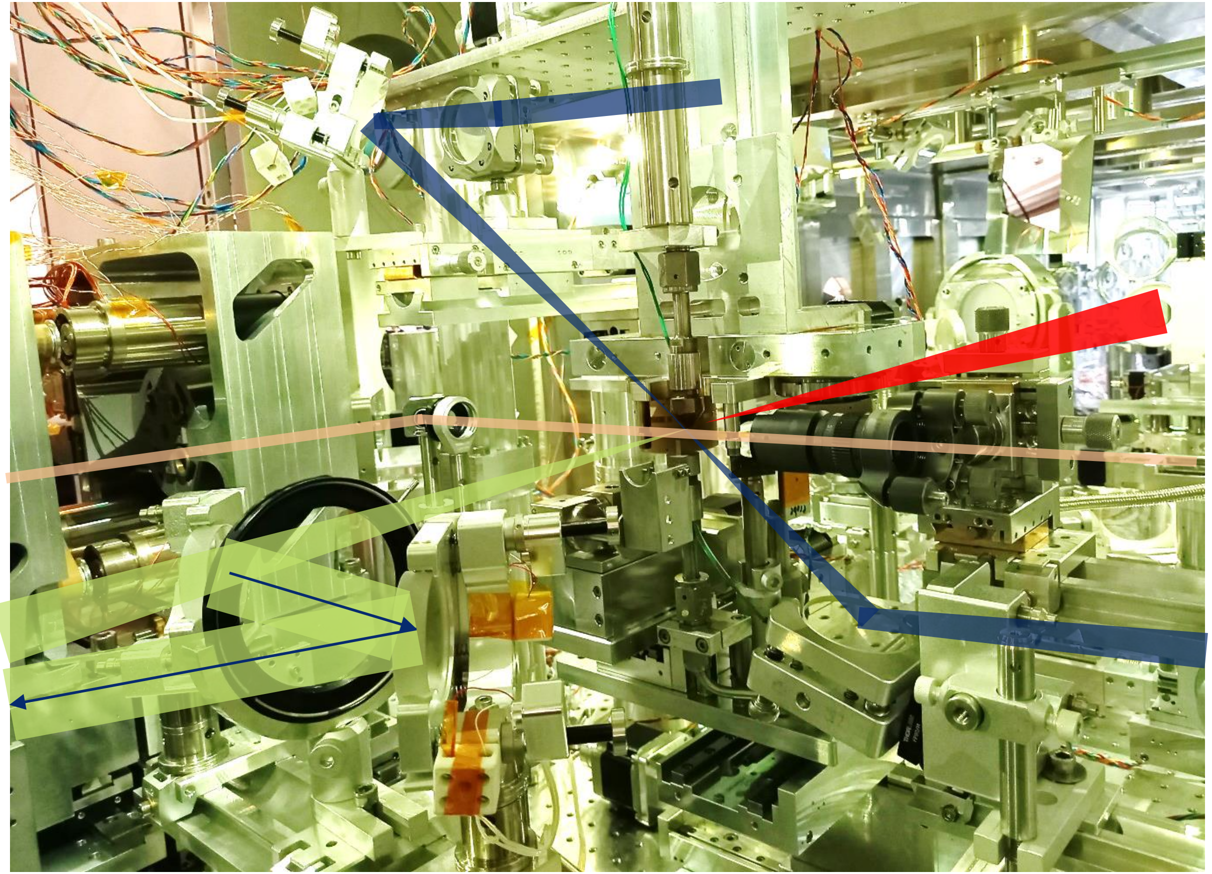

LWFA drive laser

Probe laser

Pre ionizer laser

PWFA injection laser