Recap of PWFA experiments in June 2020

- Motivation
- Course of experiment
- Evaluation of data

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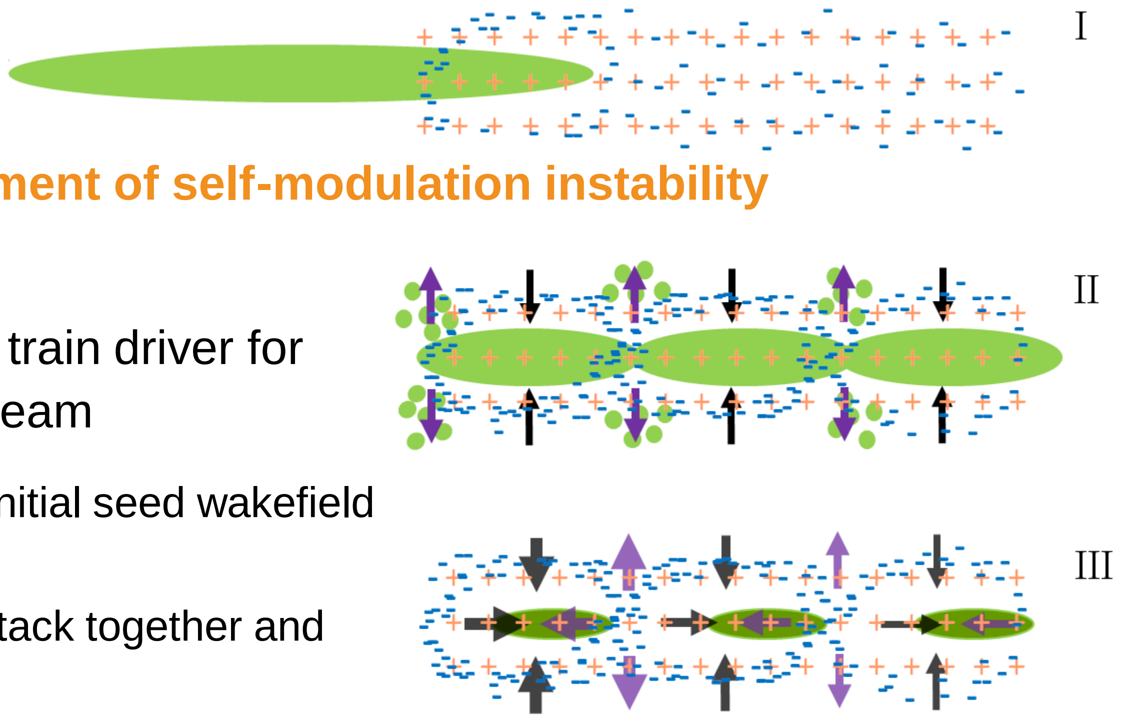
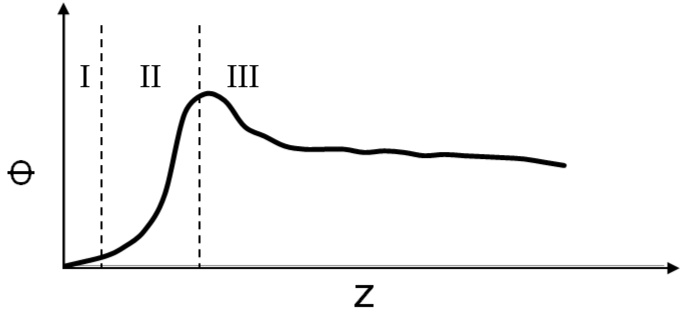
Zeuthen, 2020-08-27

Motivation

Employ cross-shaped plasma cell setup to study development of self-modulation instability

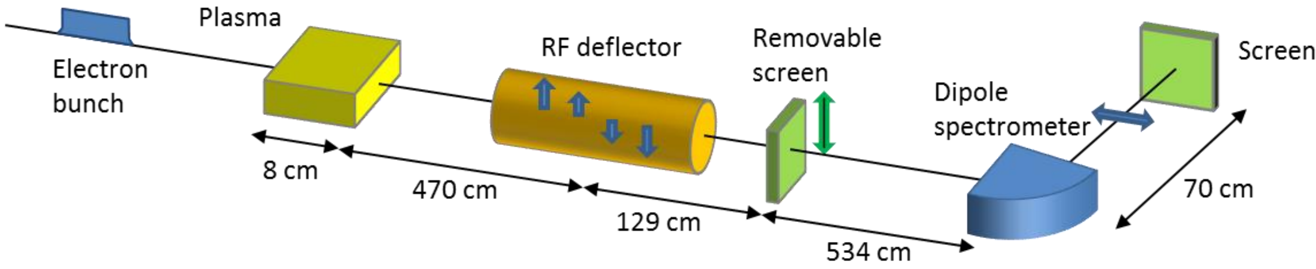


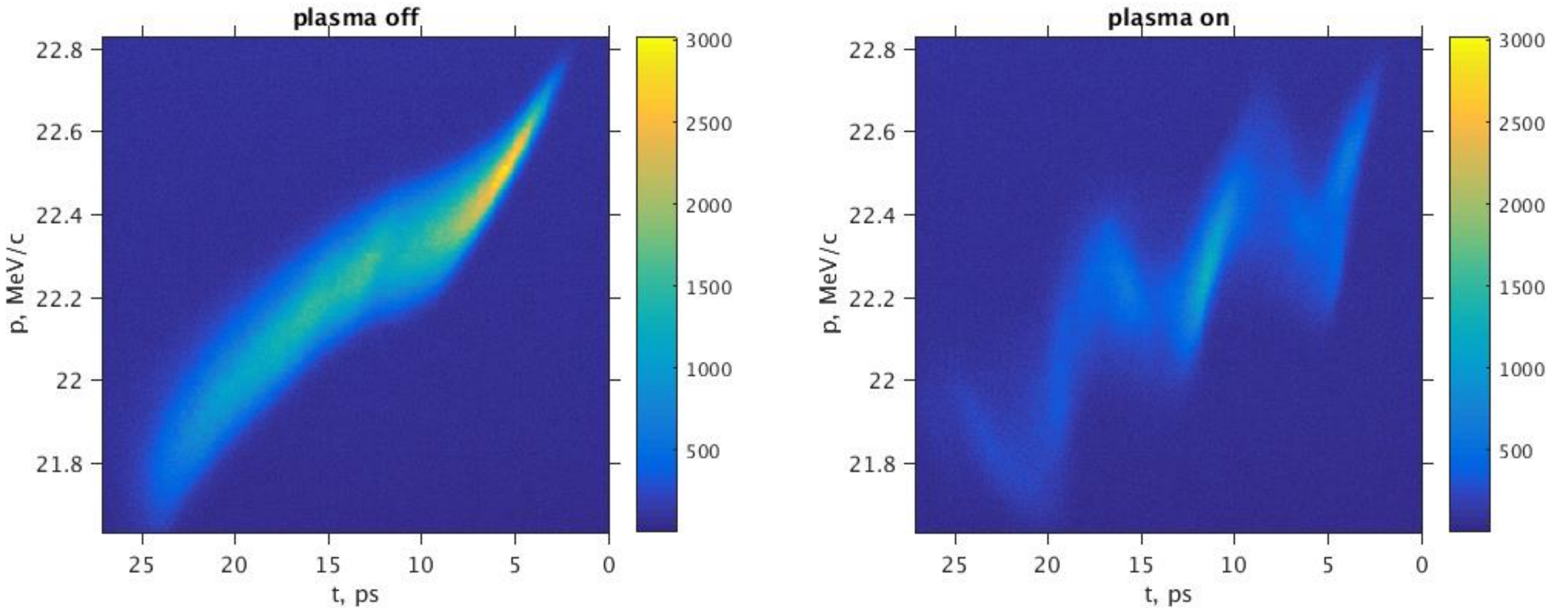
- Self-modulation instability (SMI) is way to generate a bunch train driver for plasma wakefield accelerator from a long charged particle beam
  - Long (on plasma wavelength λ scale) beam gets modulated by initial seed wakefield driven by its head
  - Charge density modulations drive secondary wakefields which stack together and amplify seed -> nonlinear growth amplitude
  - Wakefield slows down w.r.t beam during growth and catches up when modulation is completed
  - Plasma wavelength $\lambda[\mathrm{mm}] \approx \sqrt{\frac{10^{15}}{n\,[\mathrm{cm}^{-3}]}}$
  - Conditions for SMI:
    - $\boldsymbol{\sigma_z} \gg \lambda, \boldsymbol{\sigma_r} \leq \lambda/2\pi$
    - **linear regime** $(n_b/n_p < 1)$



Motivation

Previous experiments at PITZ





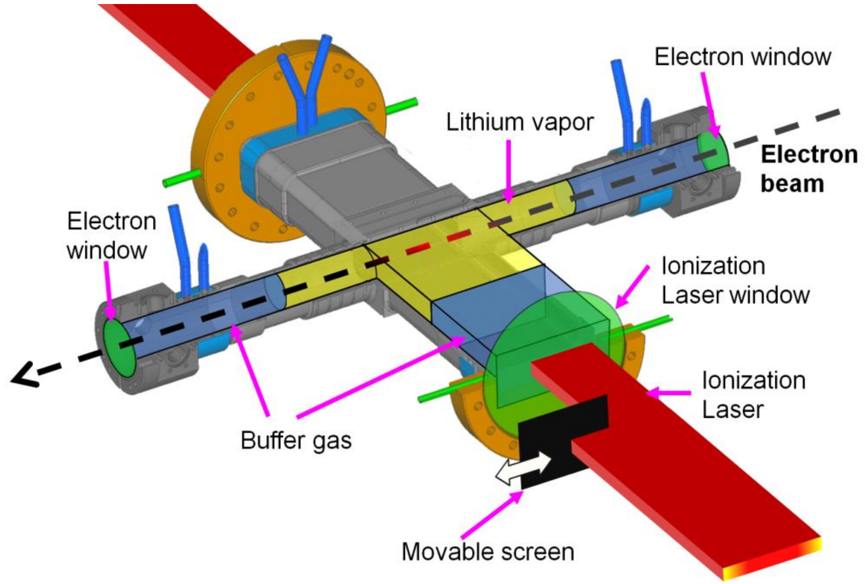
- Momentum modulation with 200 keV/c amplitude
- Low plasma density -> few modulations -> cannot claim instability growth

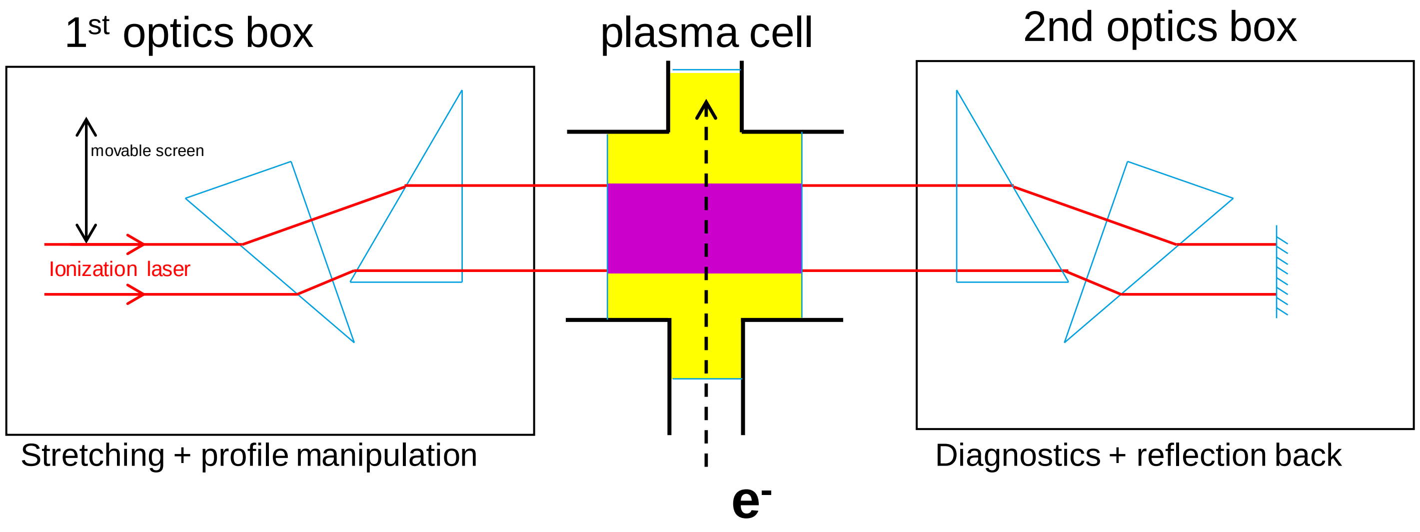
Motivation

Employ cross-shaped plasma cell setup to study development of self-modulation instability (SMI)

Setup

- Plasma is created by ionization laser coming from side -> **control over longitudinal plasma profile**
  - movable screen in front of plasma cell can block or attenuate part of the ionization laser
- Heat-pipe setup was improved to get higher lithium vapor pressure -> **plasma density up to 1x10^{15} cm^{-3}**





Motivation

Observe characteristic features of SMI

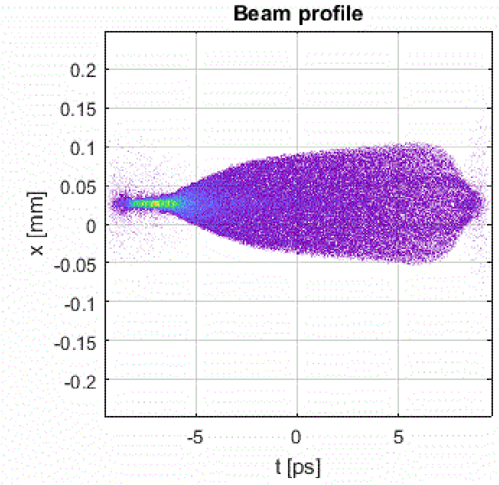
Planned experiments

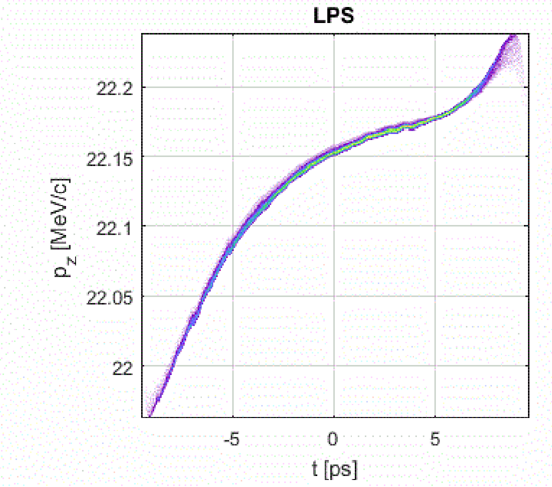
- Self-modulation versus plasma channel length -> **observe non-linear growth + dephasing** (= instability)
- Self-modulation versus density step -> **mitigate phase slippage** (= preserve more beam current)

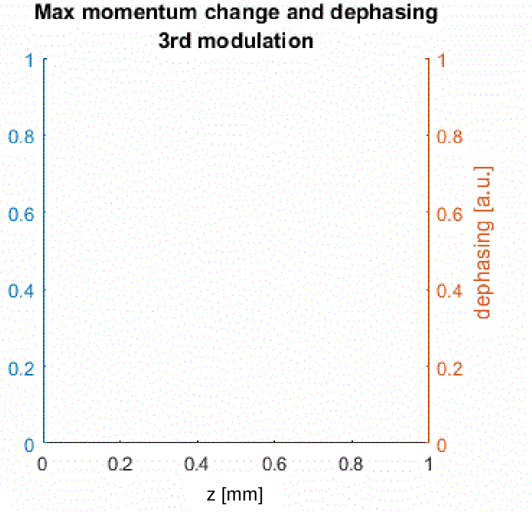
Experimental conditions acquired from simulations

- **At least 4 modulation periods** (condition for instability feedback) -> ~5x10^{14} cm^{-3} @ 20 ps long electron beam
- Growth saturation after 35-40 mm in plasma for n_p ~ 5x10^{14} - 1x10^{15} cm^{-3} (also depends on charge, focusing, etc.)

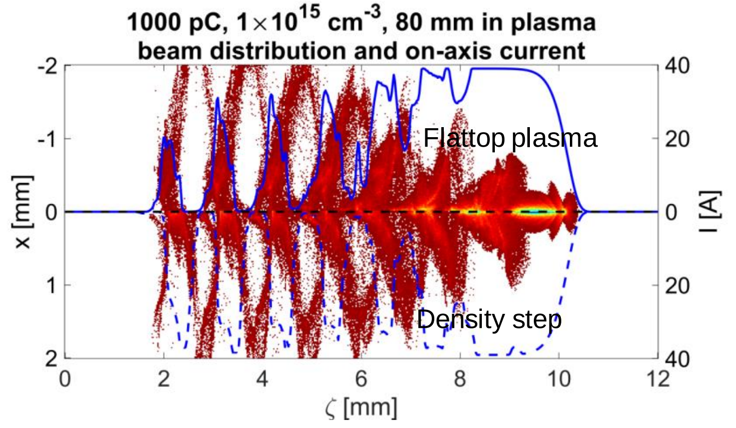
1 nC, 5x10^{14} cm^{-3} plasma:







Density step

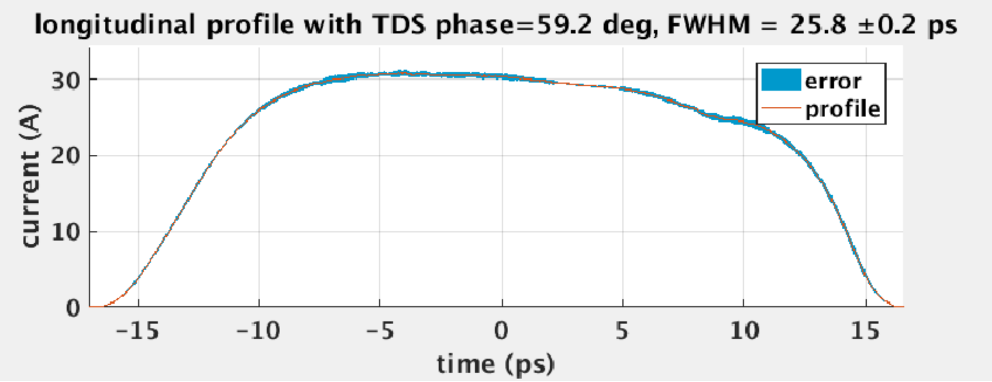


Experiment

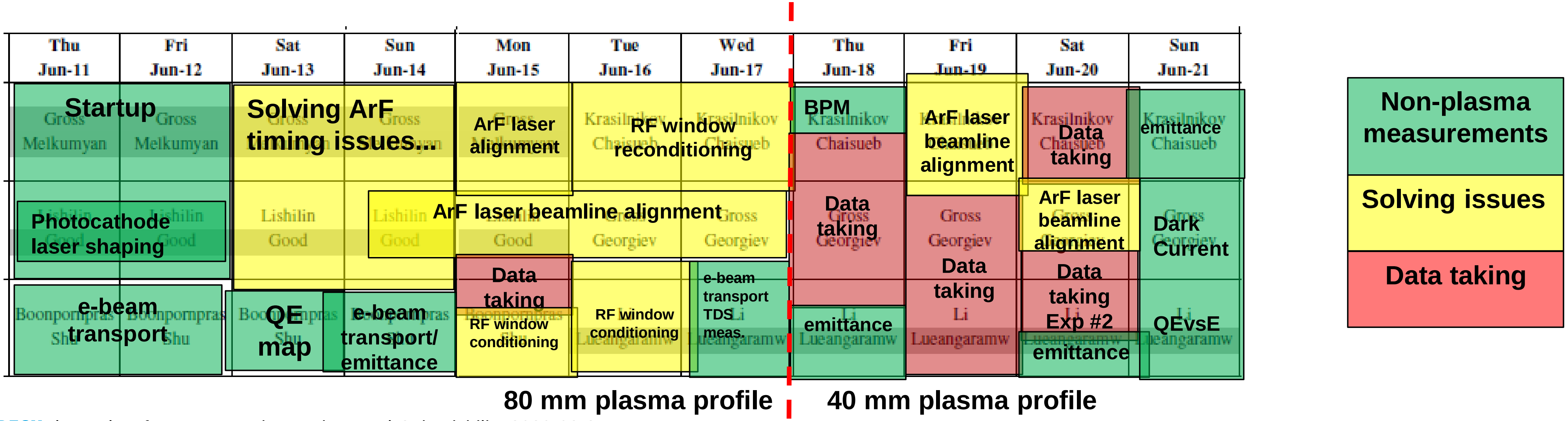
Overview of the run

- Nice flattop electron beam generated with ELLA – even longer than appreciated and quite stable and reproducible

- Initially planned up to 11 days for everything, but got delayed by several issues, mainly with **the ionization laser transport**



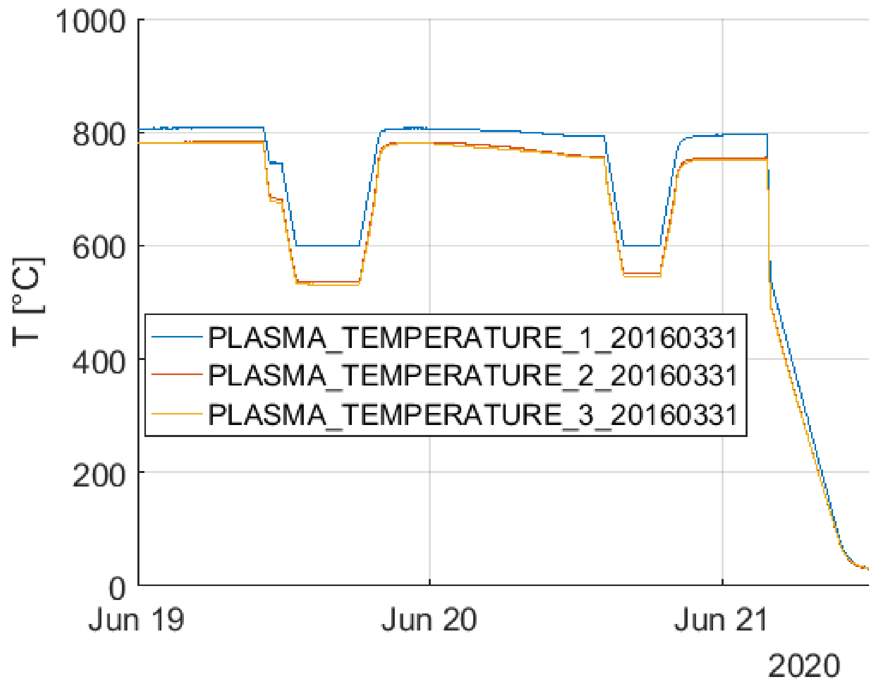
- First stable measurement of SM on the 5th day, but deduced density is below 1e14 cm^{-3}
  - Cause: high laser divergence (a lot of intensity lost on the way)
  - several improvements of laser transport made, ended up with trading off the ionization channel length for intensity.

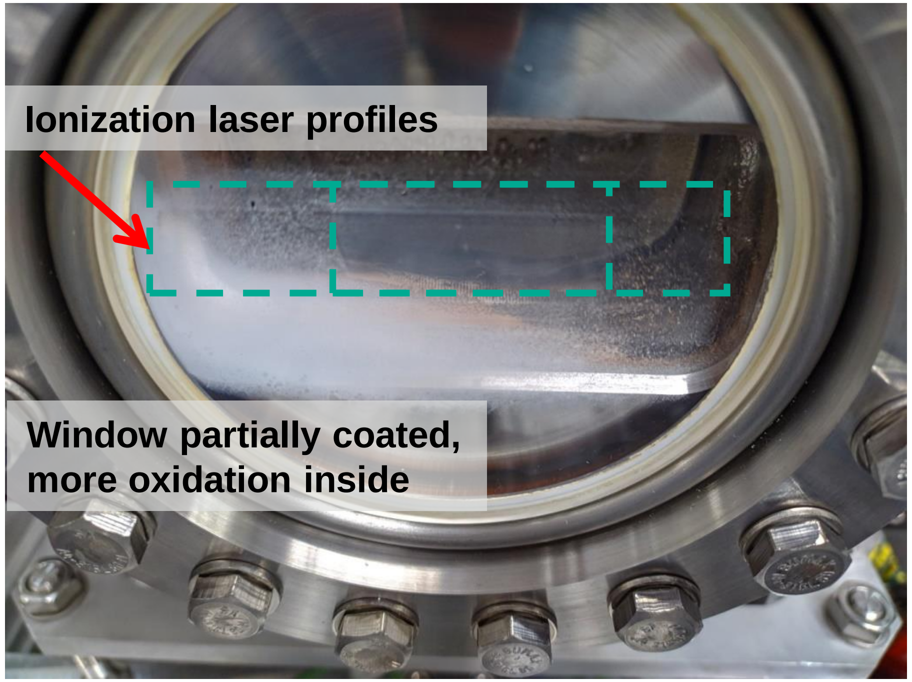


Experiment

General issues

- Issue with ArF laser trigger delay – we were trying to synchronize laser to a next 10 Hz “bucket”
- RF2 vacuum window reconditioning – problem caused by using cold startup for a short RF pulse
- By the end of the run: **oxidation on the backside ionization window**, decrease plasma cell temperature
  - caused by the leak through backside ionization window?





Experiment

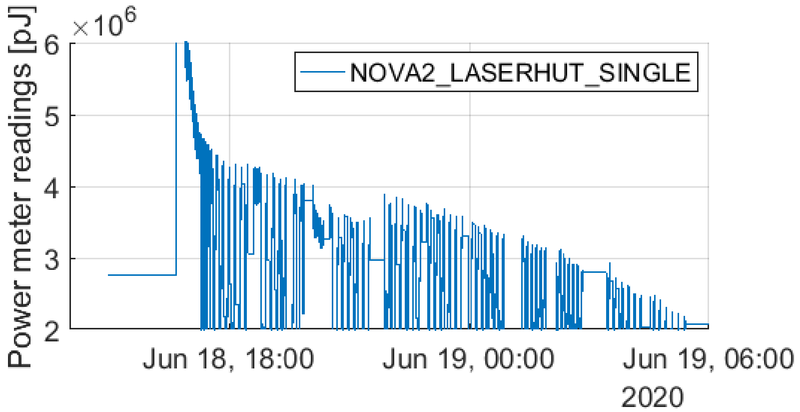
Issues related to ionization laser

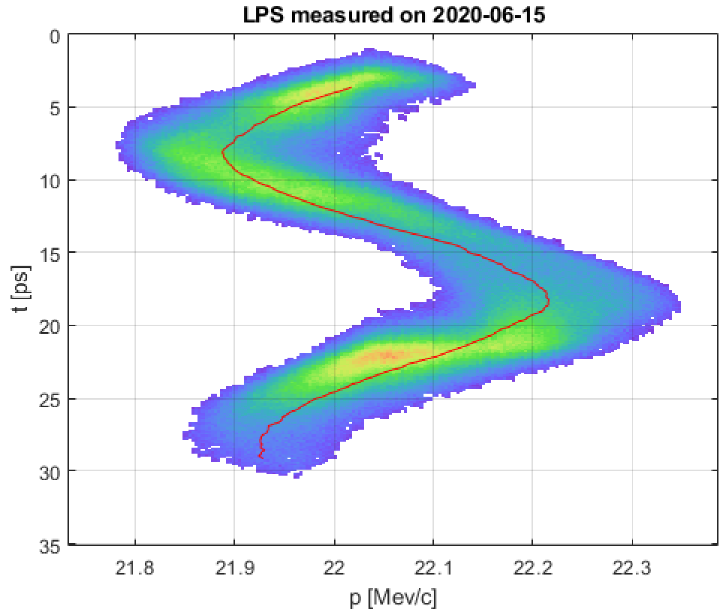
- Shortly after the previous experiment with Li plasma cell, ArF laser resonator mirrors were replaced,

  > **increased output energy**, **but also higher divergence** (we did not realize that before the experiment)

- Very small fraction of the energy delivered to plasma cell -> low plasma density (<1e14 cm^{-3})

- Beamline lost air tightness (sealing degraded due to radiation)

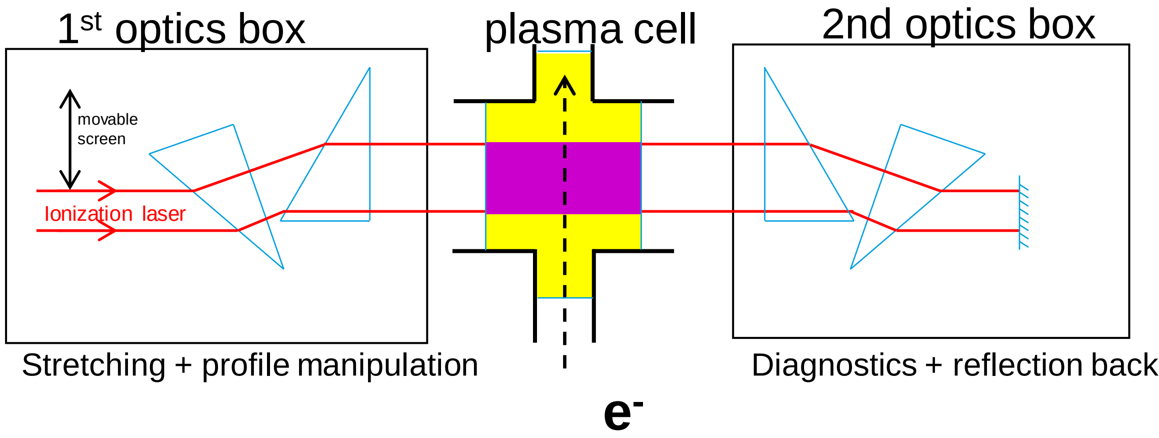




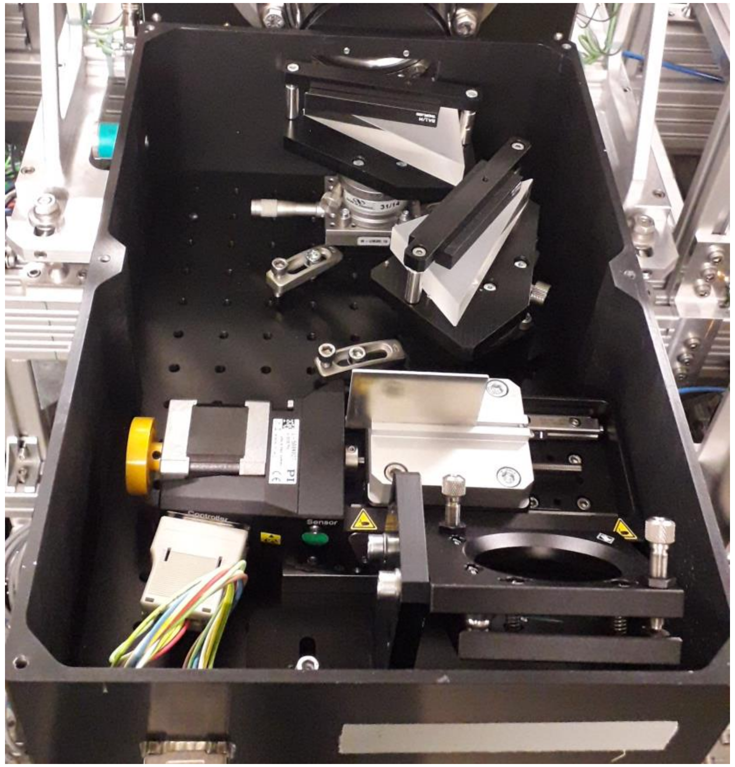
- Several improvements were made on the fly:
  - Realignment of optics in 1L18 and laser mirrors
  - Checking beamline mirror-by-mirror
  - Sealing of the optics box in tunnel replaced
  - **Stretching pair of prisms in 1st optics box replaced with mirrors**

Experiment

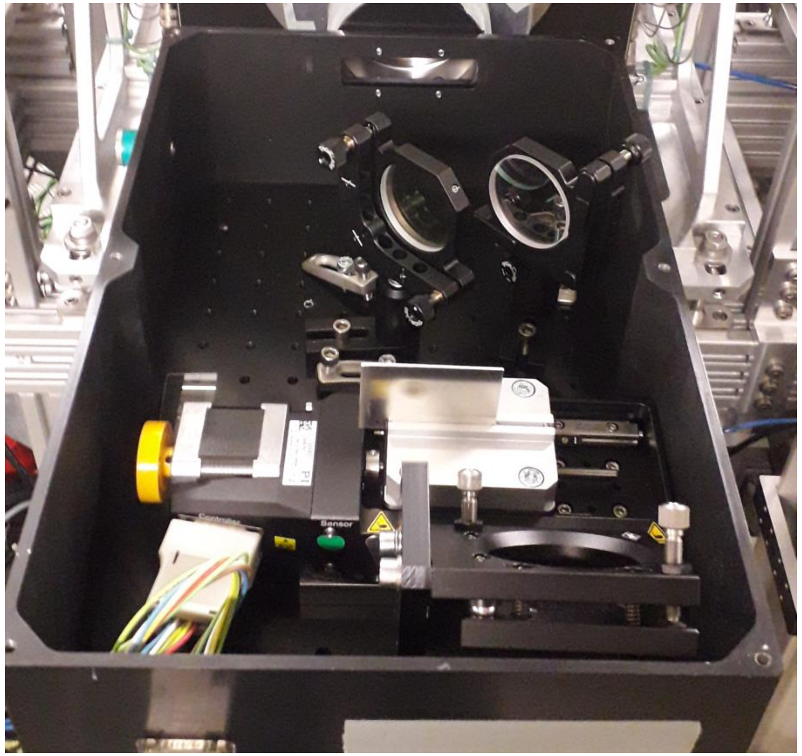
Optics boxes



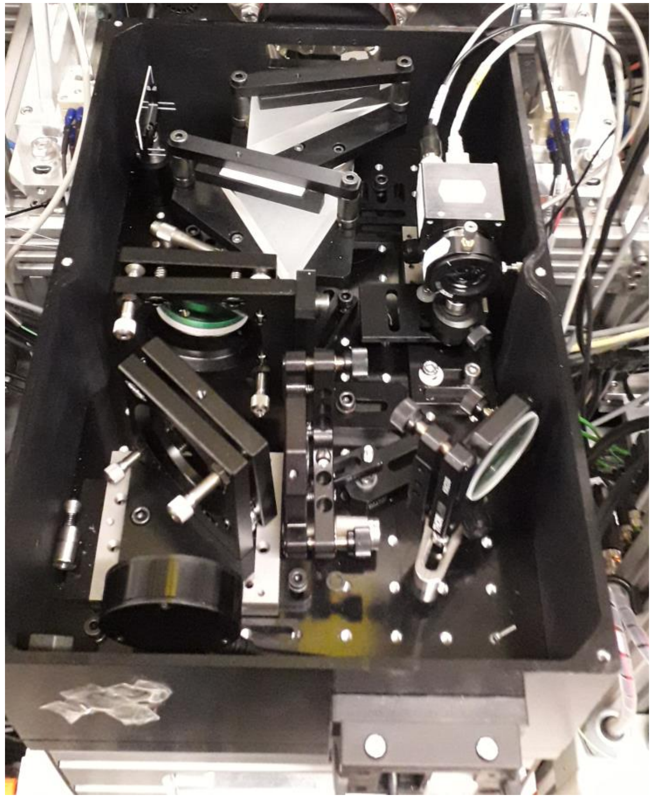
1st optics box with prisms



1st optics box with mirrors

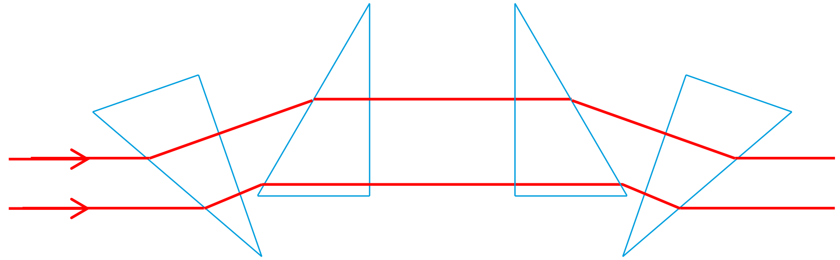


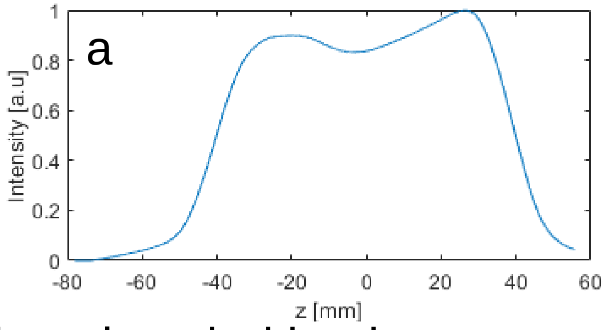
2nd optics box with diagnostics



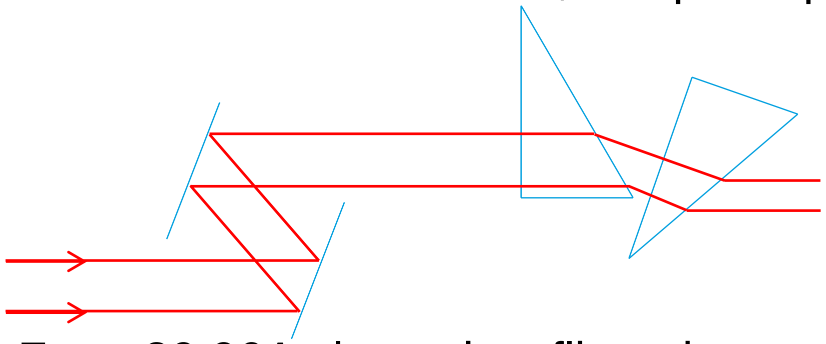
Laser profile measurements

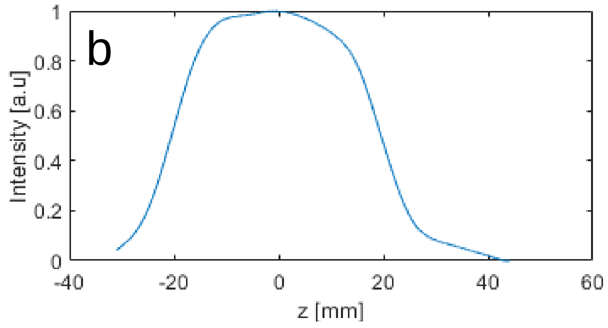
- Until 17.06A: 80 mm laser profile



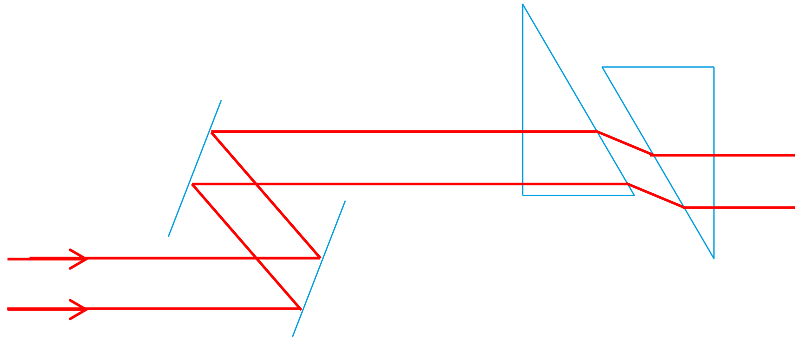


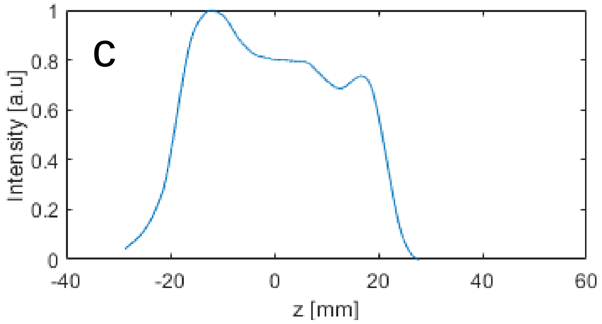
- 17.06A – 20.06A : 40 mm, first prism pair replaced with mirror

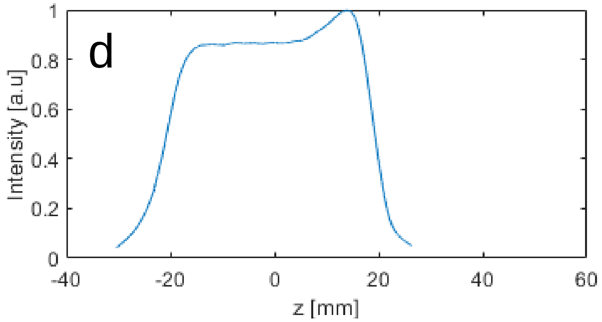




- From 20.06A : last prism flipped







- b & c – same laser profiles, only prism arrangement changed
- initial setup: path length through the prisms is not equal across the profile > ΔLT = 7%
- flipped prism: same path through the prisms
- **Measured profile skewness ~20%**

Data taking

Experiment #1

- Long laser profile (a): 1 nC vs I_{main}
- Shorter laser profile (b <-> c): [1, 0.8, 0.6, 0.4] nC vs Imain
- Shorter laser profile, straightened (d): 1 nC vs I_{main}

Experiment #2

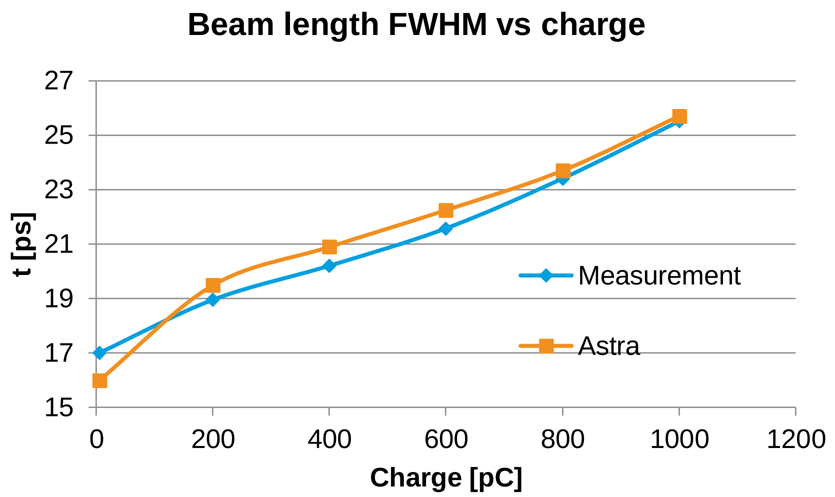
- Shorter laser profile, straightened (d): [1 0.75 0.5 0.25 0.1] nC vs I_{main}

Ways to estimate plasma density:

- Plasma wavelength $\lambda[\mathrm{mm}] \approx \sqrt{\frac{10^{15}}{n\,[\mathrm{cm}^{-3}]}}$
- Inferring frequency from Fourier spectrum (see G. Loisch, https://doi.org/10.1088/1361-6587/ab04b9)
- Matching number of modulations with simulations

LPS saved for different plasma channel lengths **-> can estimate the plasma density variation along the channel**

Simulation strategy



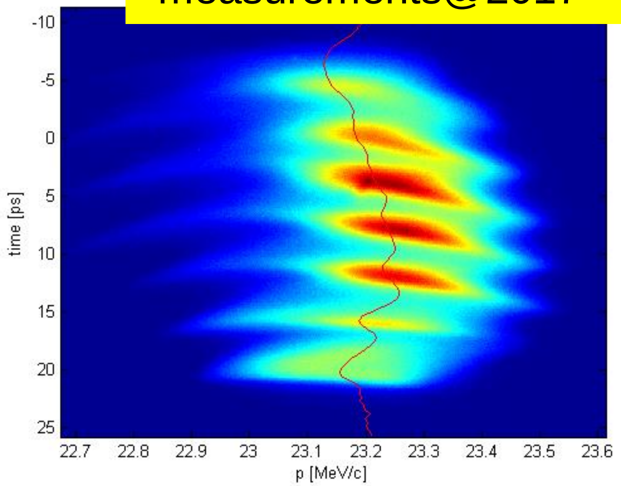
- Transport beam to plasma cell with ASTRA
  - Match FWHM bunch length
  - Same quadrupoles as in experiment
- Simulate beam-plasma interaction with HiPACE
  - Use measured ArF laser profiles (fit measured profiles to 40/80 mm FWHM)
- Fit modulation pattern to get plasma density, then look for mean momentum modulation
- Simulated 1 nC beams as they are the longest
- Tuning knobs: solenoid focusing, plasma density

	Measured	Astra
Q, nC	1	1
γ	43.6	43.2
$\Delta p/p$, %	0.8	1.5
$\sigma_{x/y}$, mm	<0.1 (best)	0.06-0.2

Data evaluation

LPS chromaticity correction

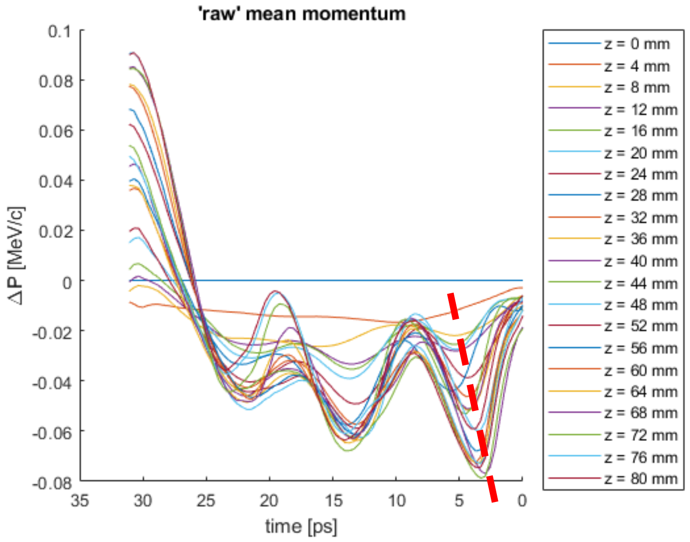
LPS from gas discharge measurements@2017

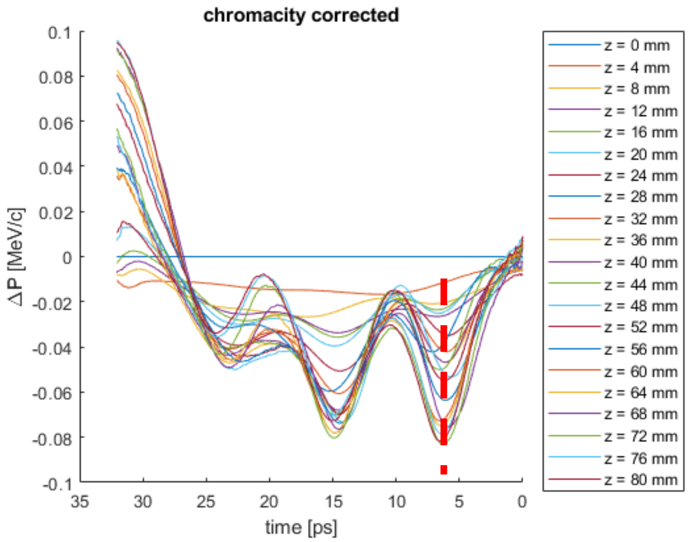


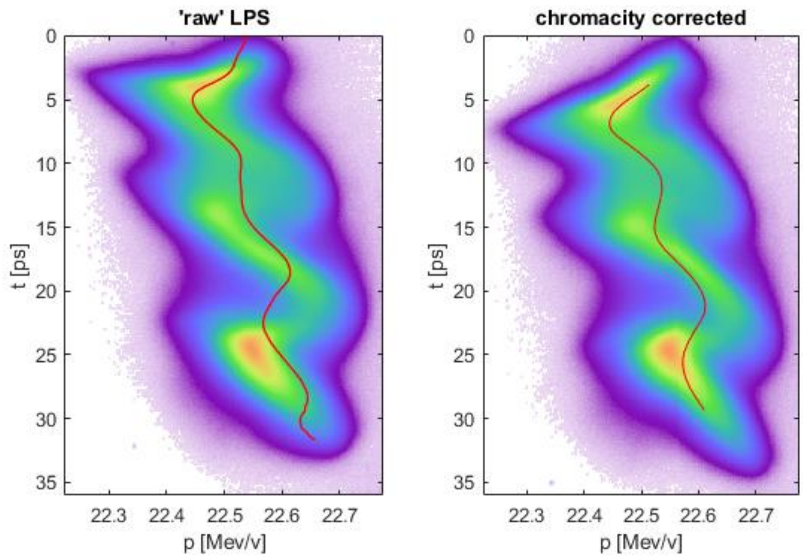
- Energy spread results in warping of LPS -> overlap of the temporal slices
- Can be corrected with a temporal offset $\Delta t = a \cdot (E - \bar{E}) - b \cdot (E - \bar{E})^{2}$,

where *a* and *b* are empirically determined

  - criteria: make sure seed wakefield does not travel forward

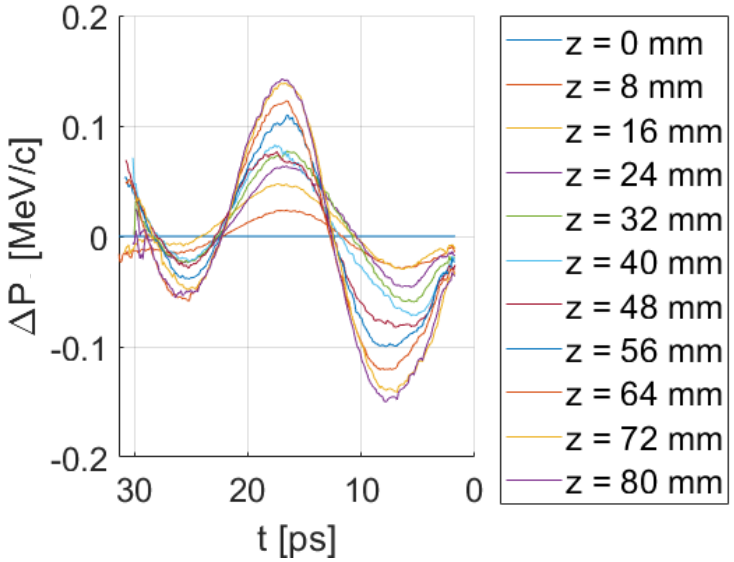


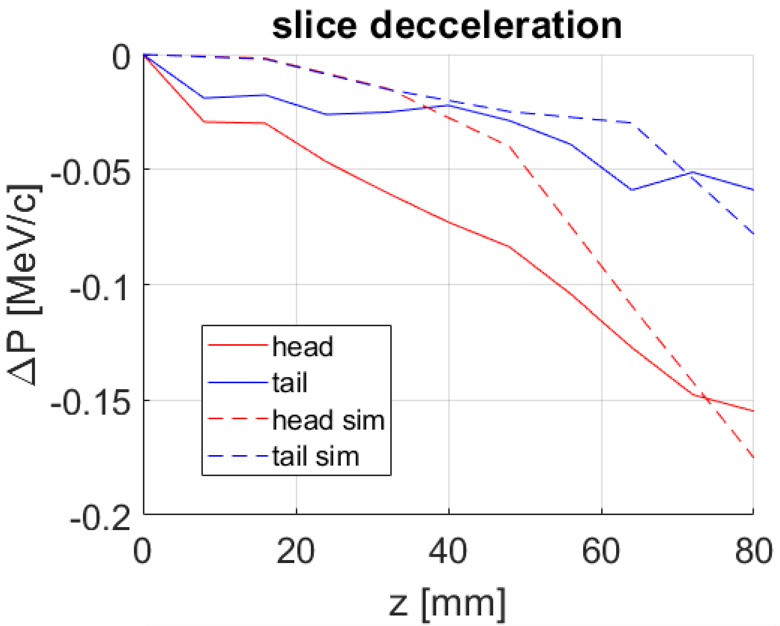


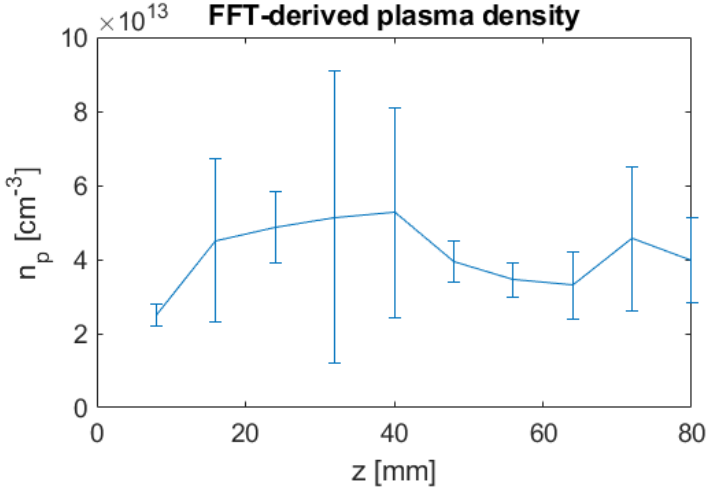


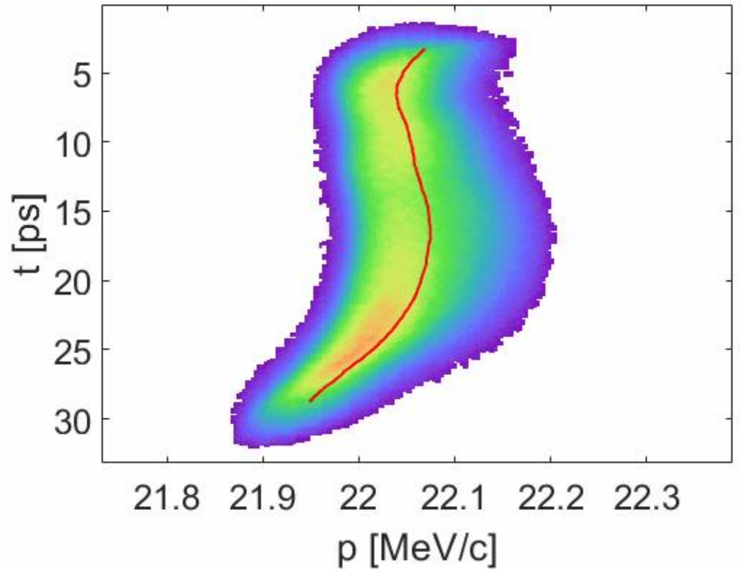
dataset#1 n_p = 5e13 cm^{-3}

Long plasma channel (a), low density





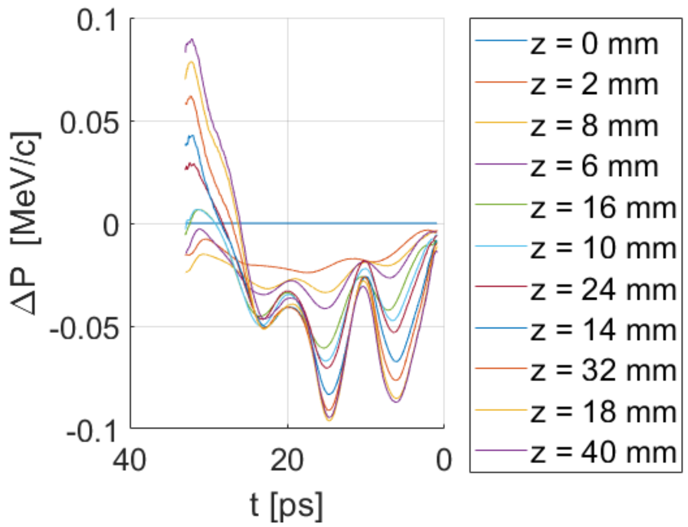


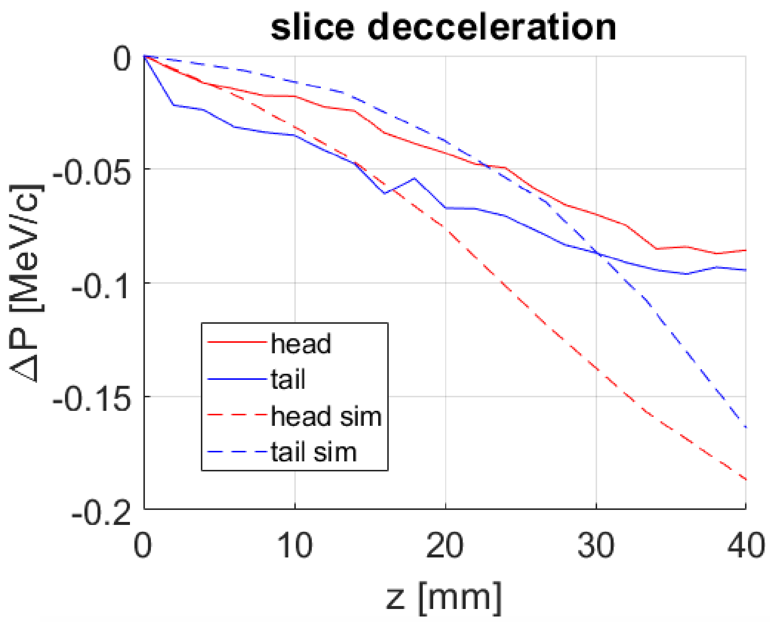


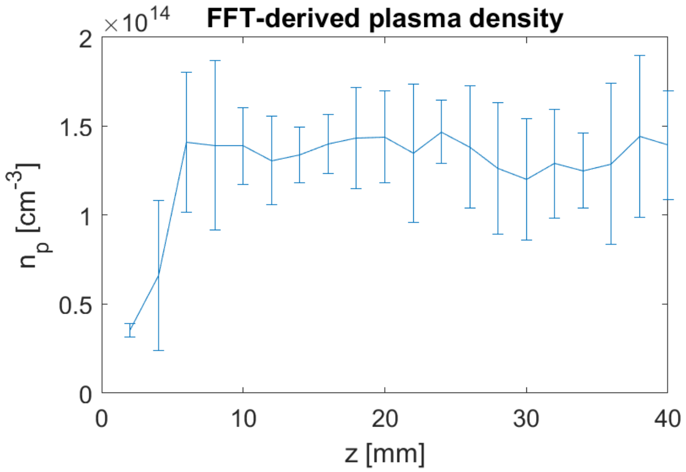
Mean over all 1 nC measurements

dataset#2 n_p = 1.4e14 cm^{-3}

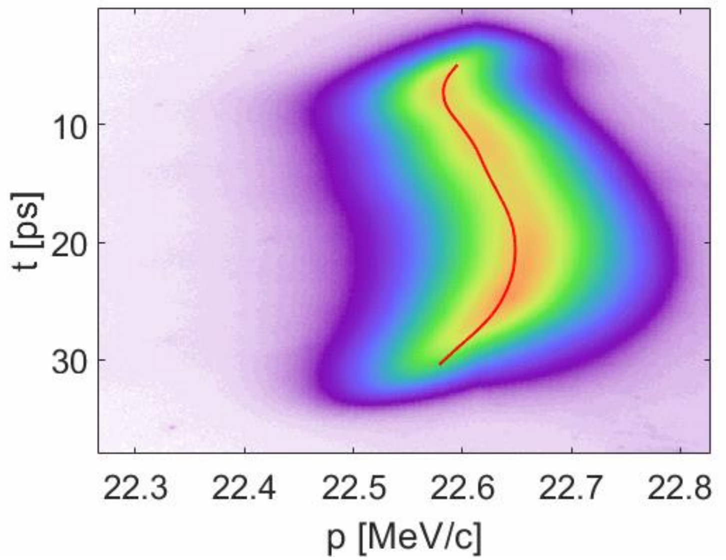
Short plasma channel (b<->c), higher plasma density





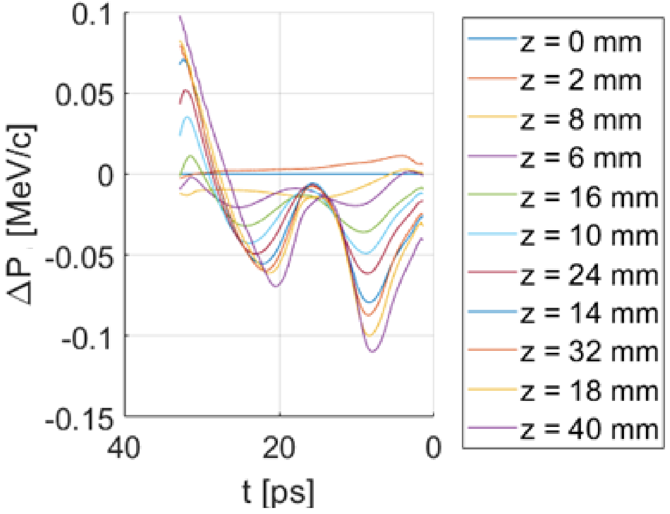


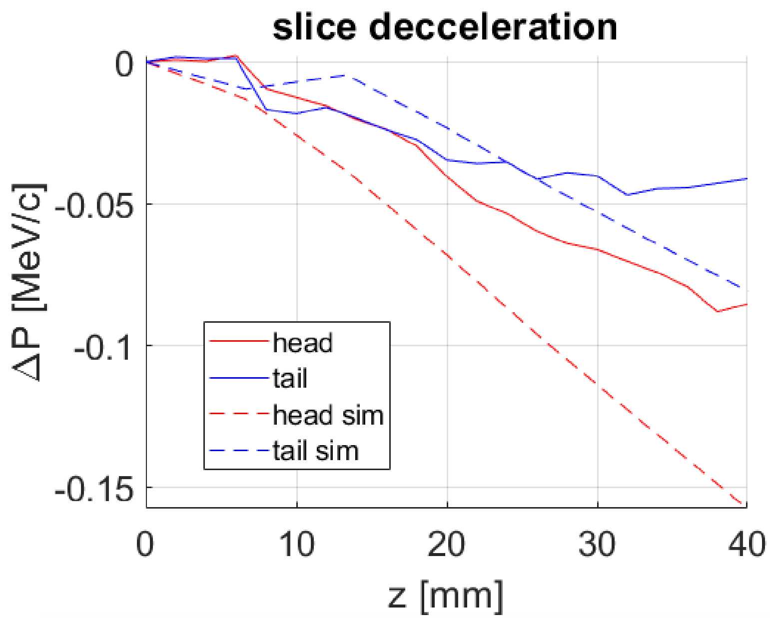
Mean over all 1 nC measurements

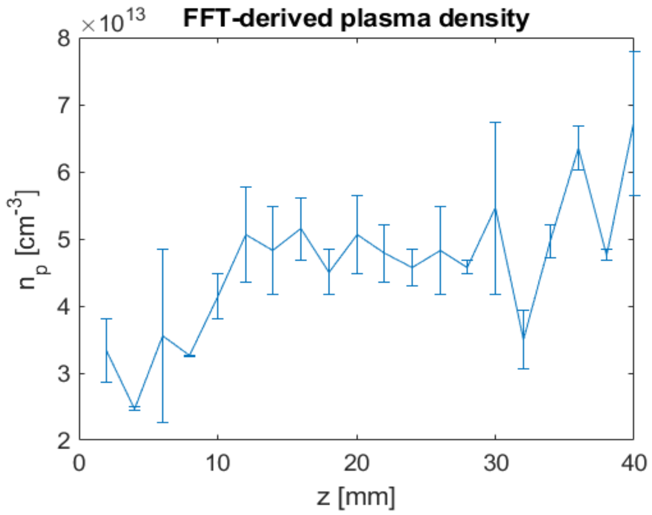


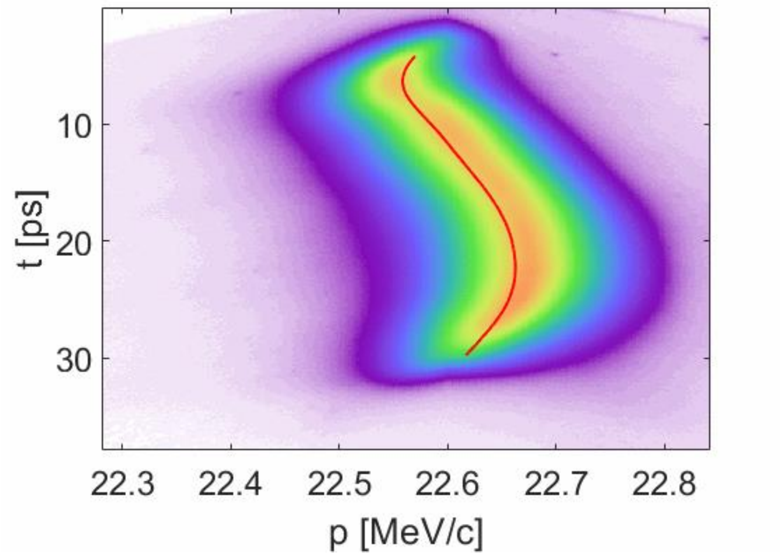
dataset#3 n_p = 7e13 cm^{-3}

Short profile (straightened)









Mean over all 1 nC measurements

Conclusions

- **Demonstrated ability to manipulate plasma channel length**
- Observed self-modulation of electron beam passing through plasma with nearly linear amplitude growth
- Laser profile measurements do not agree well with FFT-based plasma density profile measurements
- FFT-based density measurements agree with simulations
- Low plasma densities during experiment: 5e13 cm^{-3} – 1.4e14 cm^{-3}. **No conditions for SMI**:
  - Not enough modulation periods within electron bunch to form the instability feedback
  - Too short plasma channel length (in terms of plasma length units)
  - For very low plasma densities: non-linear regime ($n_b/n_p > 1$)

- Further steps:
  - Finish density step simulations
  - Look for slice energy spread?