Operation of the electron beam for external off-axis injection, electron beam seeding and hosing in AWAKE Run 2b (2023-2025)

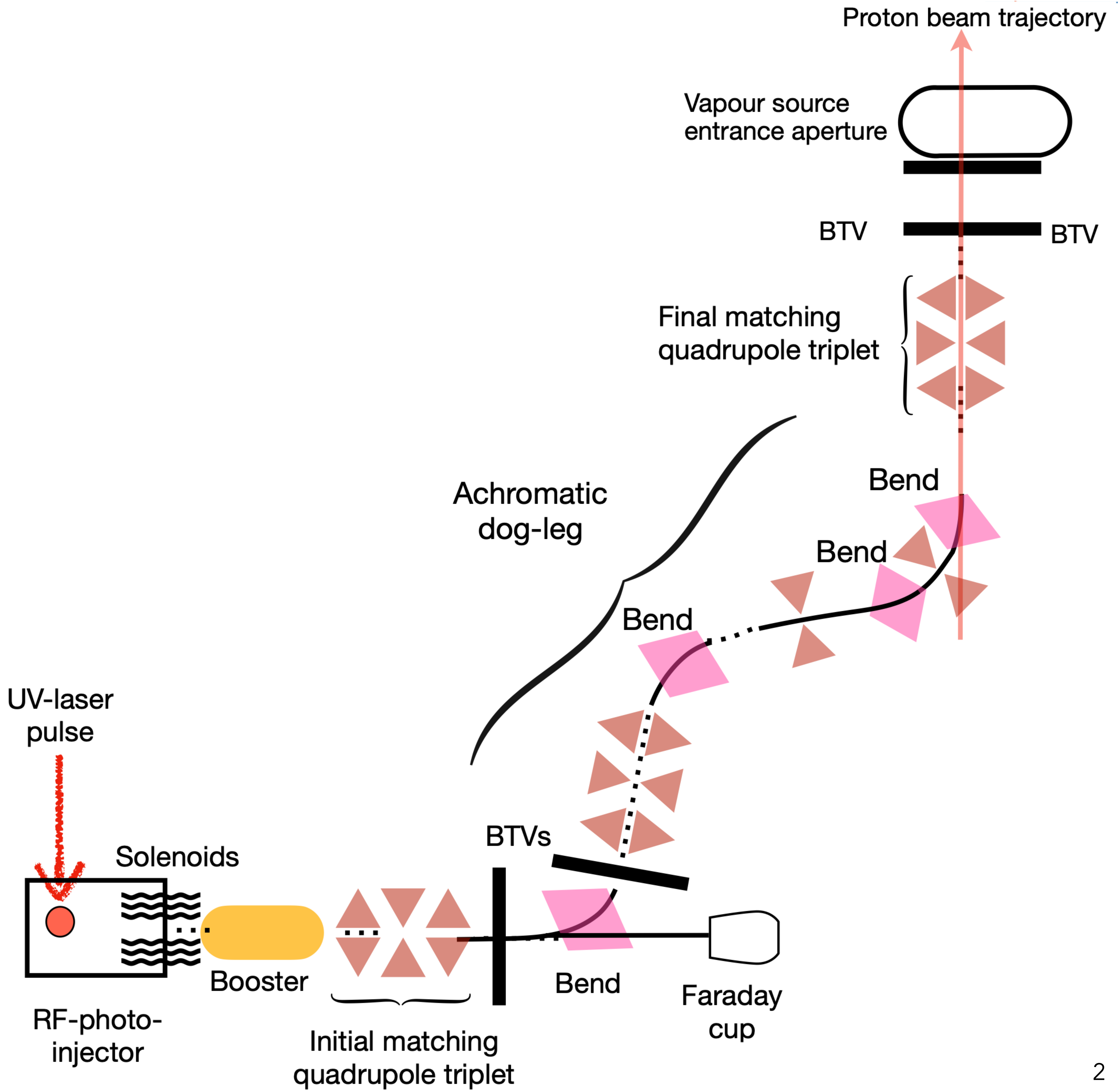
AWAKE Collaboration Meeting, November 6th-8th, CERN, CH

Nikita Z. van Gils

In Run 2b the 19 MeV electron beam has been used for …

I. Seeding of the self-modulation
II. Seeding of the beam-hose (hosing) instability
III. External injection of electrons into wakefields

Reminder: AWAKE electron gun and beam transport line



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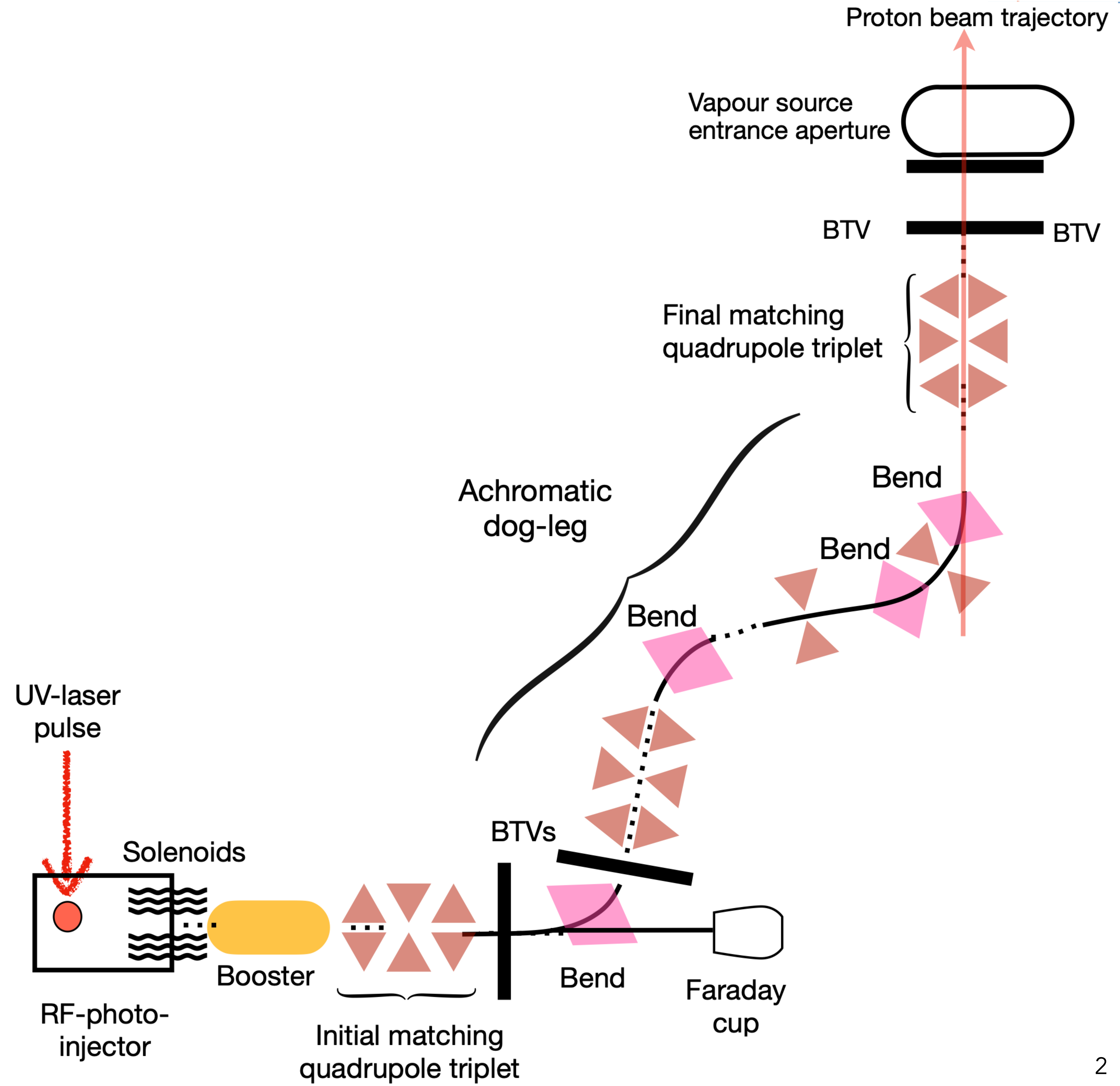
Reminder: AWAKE electron gun and beam transport line

Electron production:
illumination of Cs_2Te photo cathode with a UV laser pulse



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Input beam characterisation:
transverse emittance and bunch charge measurement

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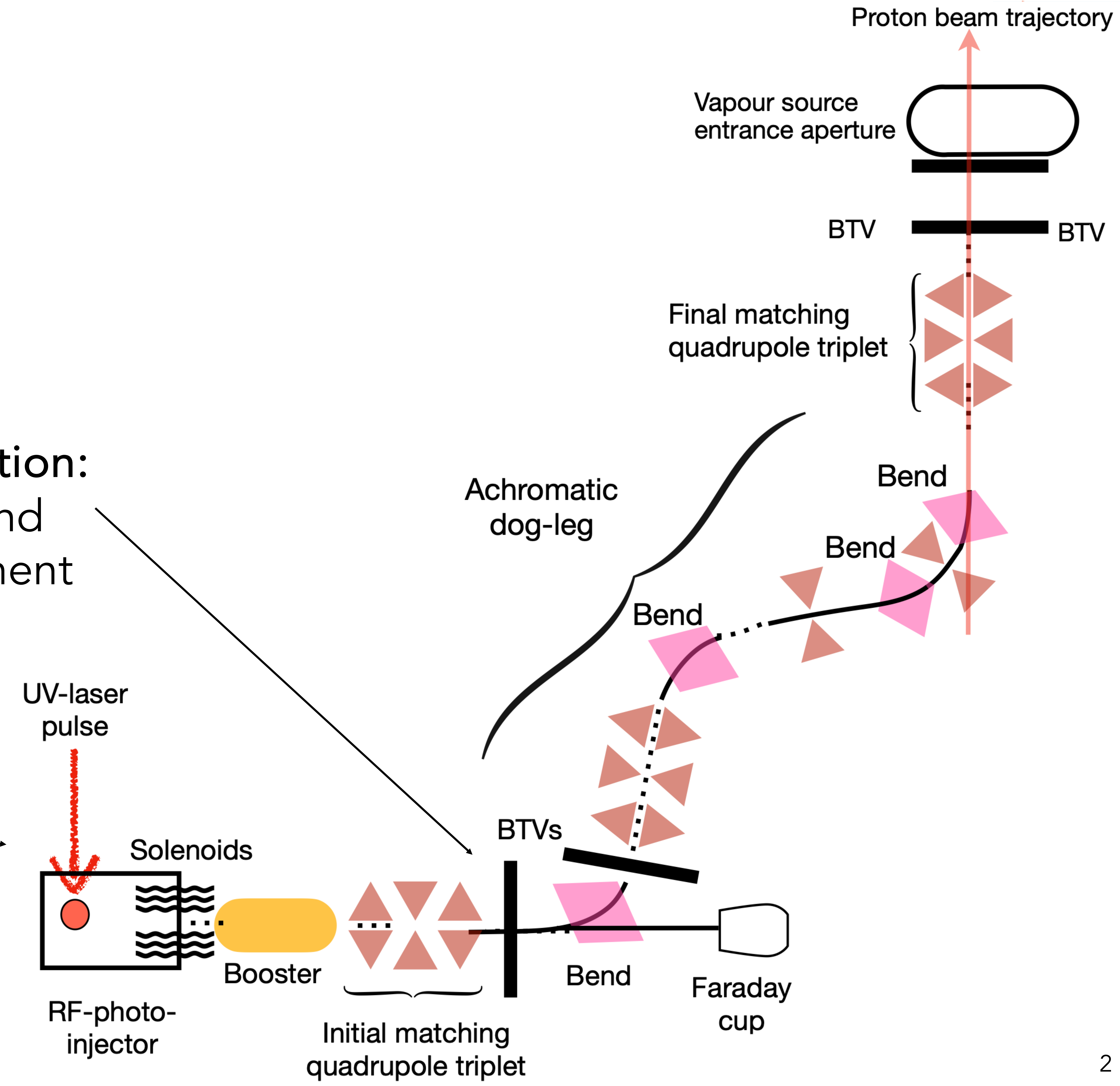

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Reminder: AWAKE electron gun and beam transport line

Transport and focusing:
initial and final quadrupole triplet to transport the beam and focus it at the location of injection

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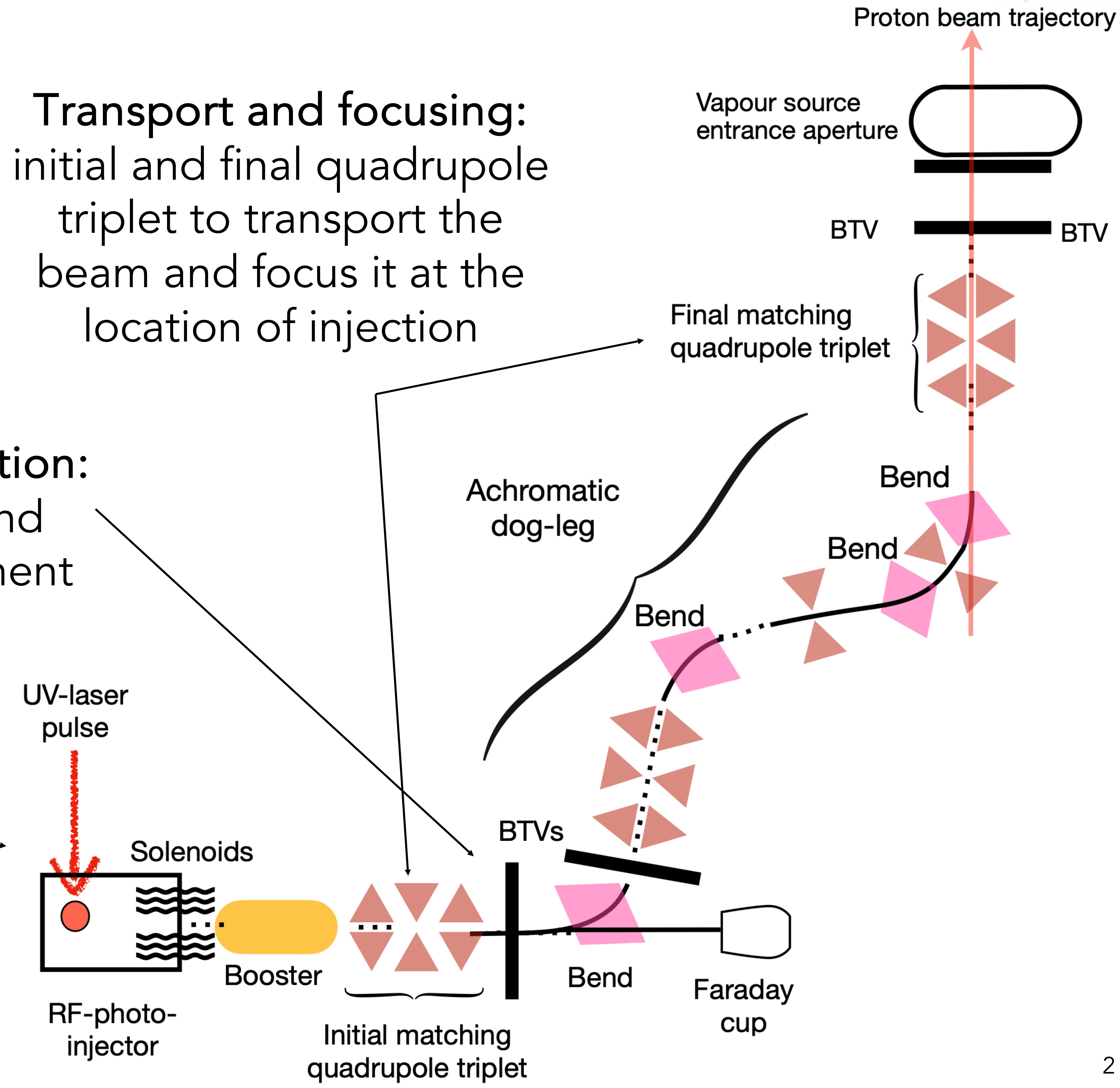
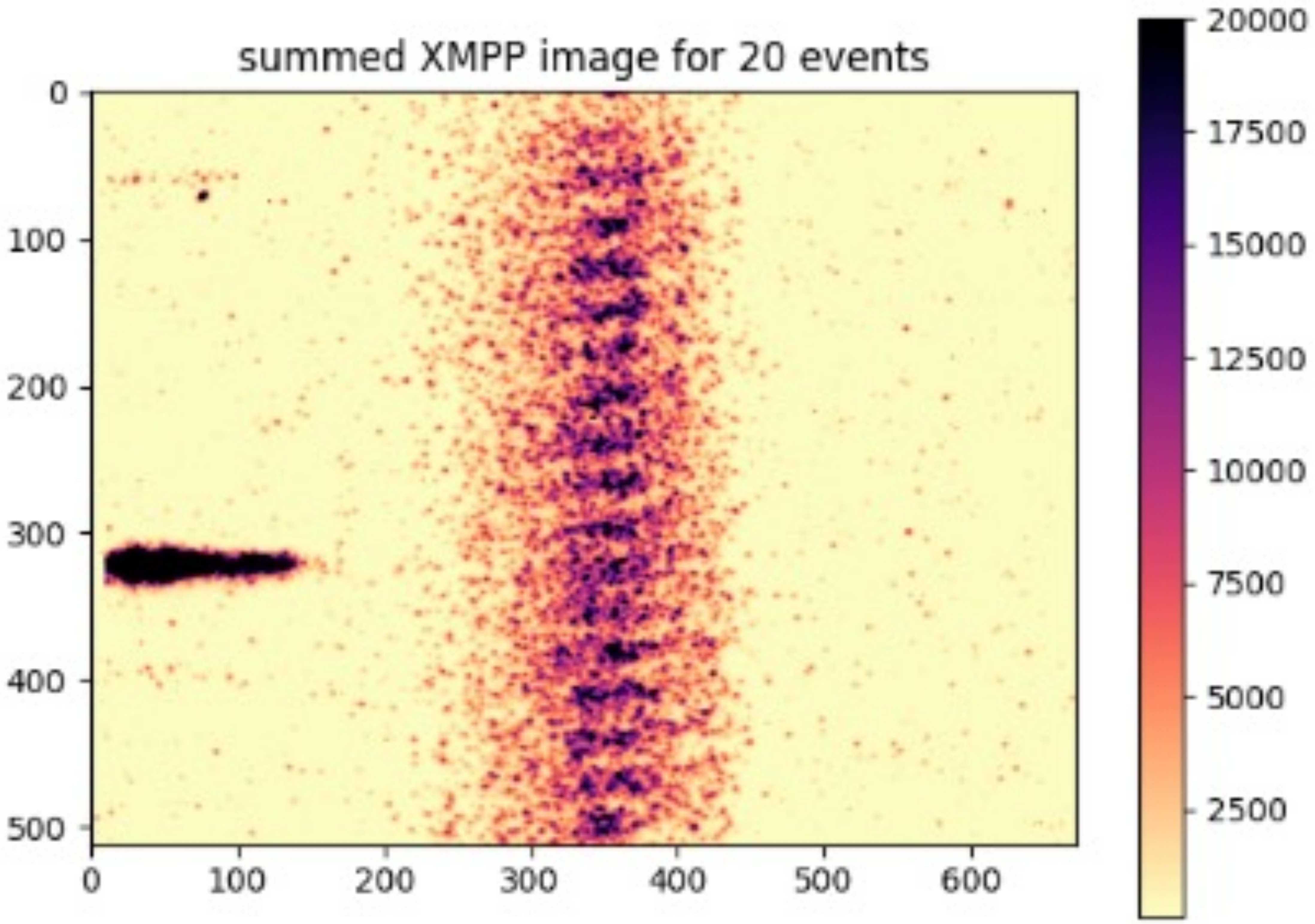
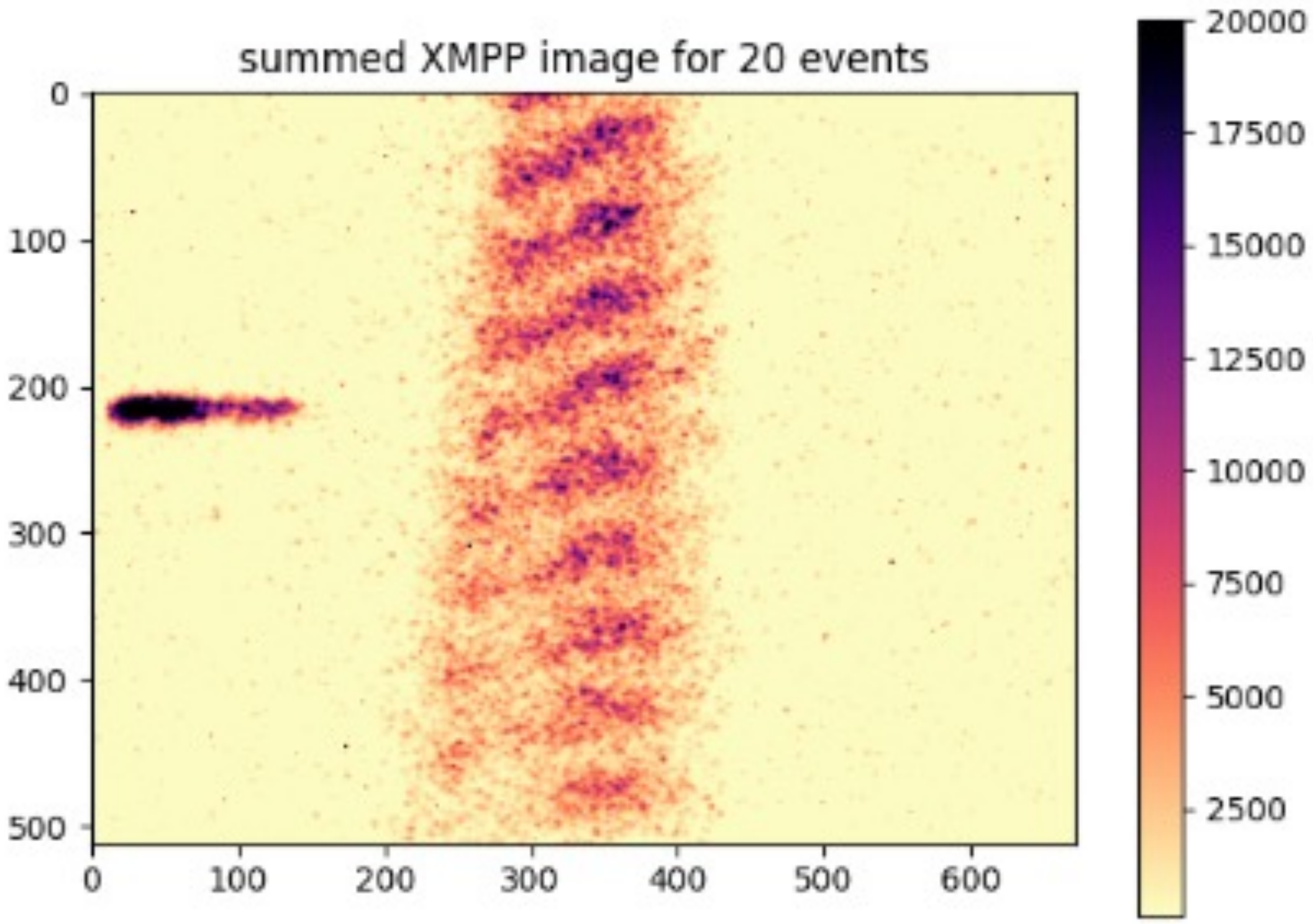


New screens enable beam measurements inside of the vapour source

For the first time, AWAKE is able to:

1) Align the electron beam to the proton beam trajectory (in vacuum) within the vapour source
2) Ensure overlap (crossing) of electron bunch trajectory with the plasma and proton bunch trajectory in vacuum
3) Maximise electron bunch charge density at z_e → screens enable transverse beam size measurements and tuning of optics and waist location
4) Set and record the electron bunch injection angle θ_i (by using also a second screen upstream of the waist location)



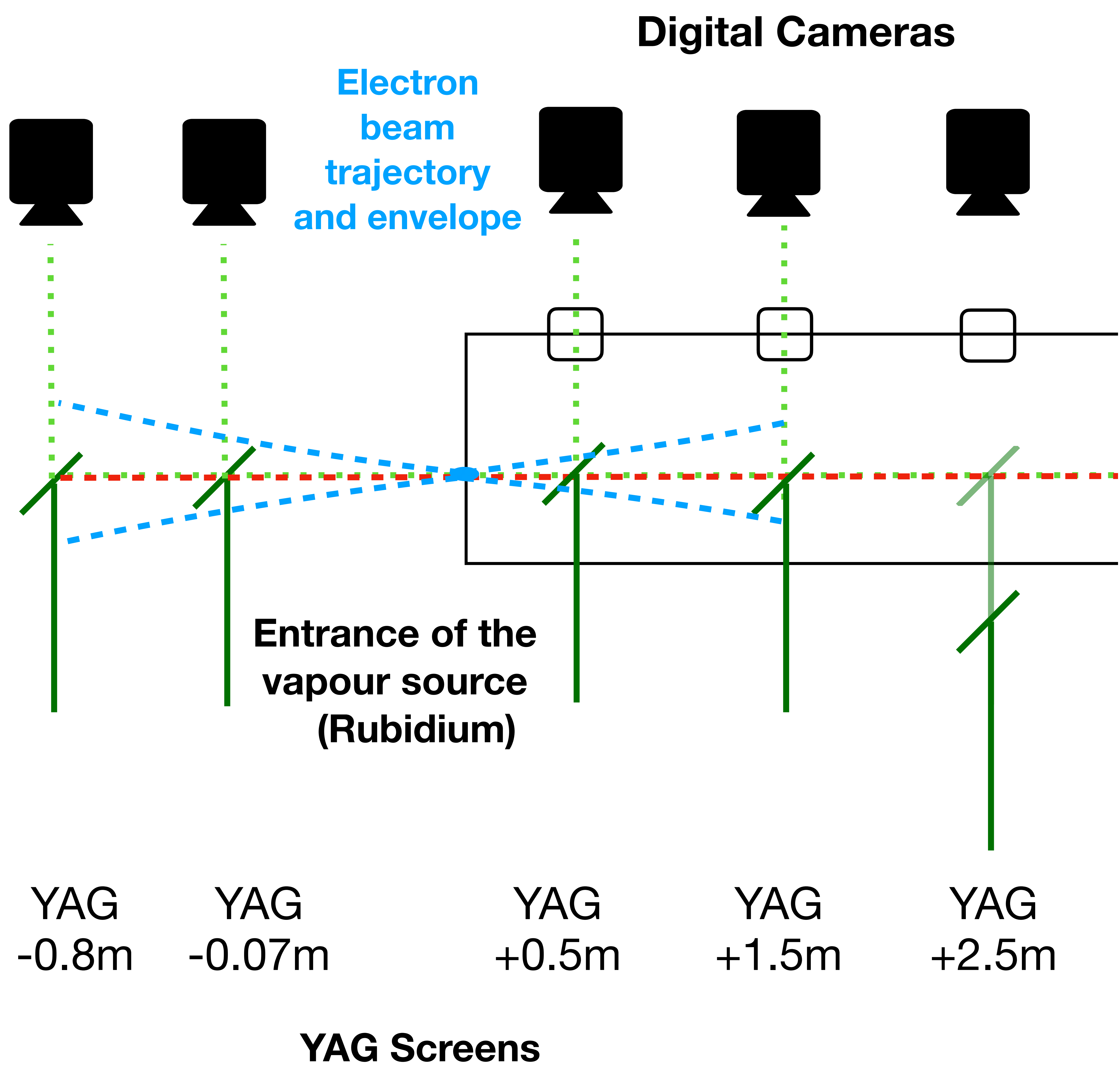


Seeding of self-modulation and hosing

Seeding of the self-modulation (SM) and hosing process

For this the electron beam should be:

- shorter than λ_{pe}: used 200 pC → ~3 ps rms length
- focused at the entrance of the vapour source
- of symmetric transverse distribution (see next slide)



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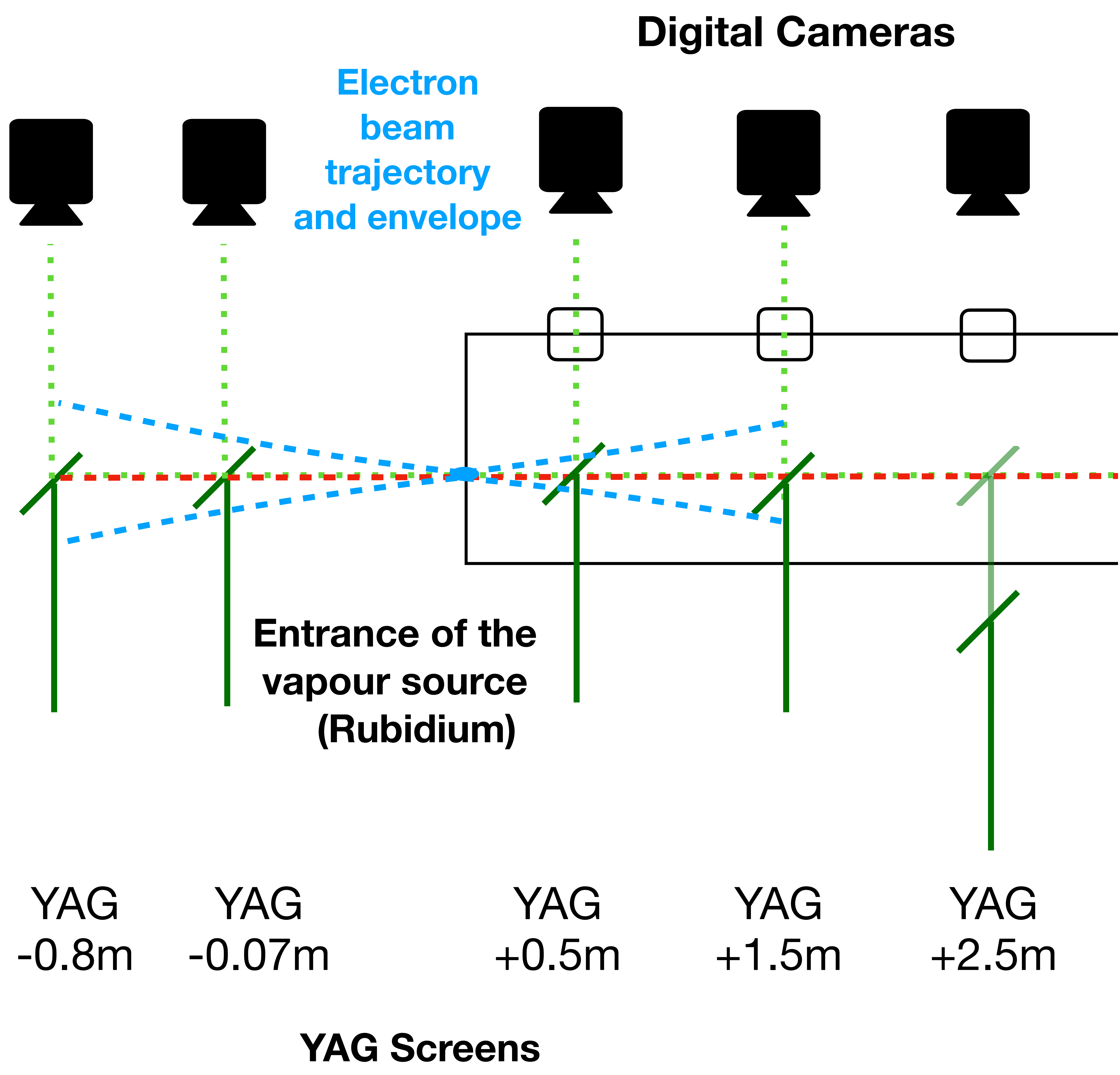
Seeding of SM:

- aligned on the proton bunch trajectory (on axis) using YAG +0.5m and YAG +1.5m

Seeding of hosing:

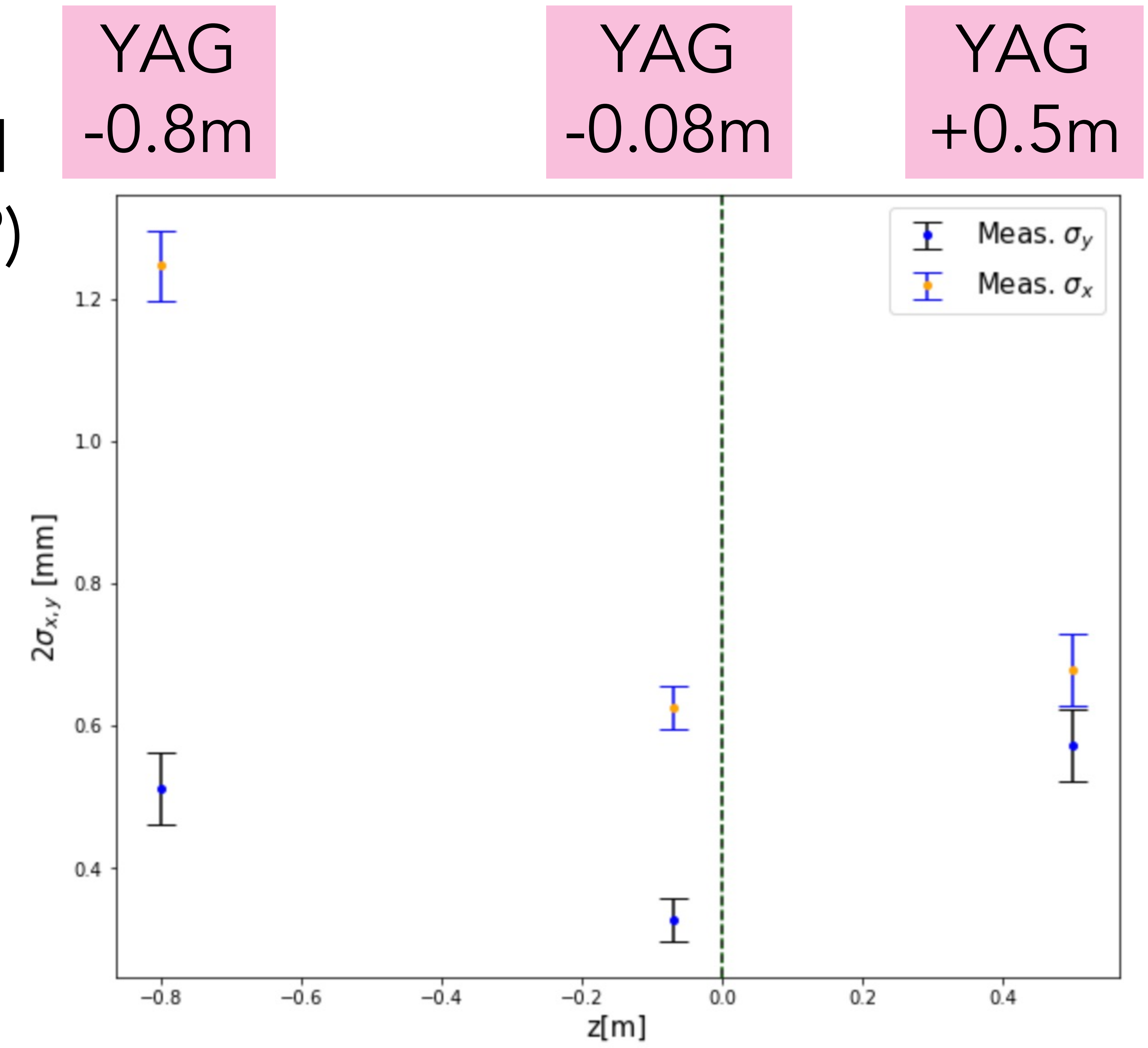
- induced by (parallel) transverse displacement of the proton bunch w.r.t. the electron bunch (as was done in Tatiana's work) => See Michele's talk



Alignment challenges

Non-symmetric transverse distributions on YAG +1.5m:

- Difficult to determine beam centre due to large horizontal beam size (due to dispersion), tails and multiple maxima (which one should we align to..?)



Beam envelope, errorbars are variations in beam size and error on the fit.

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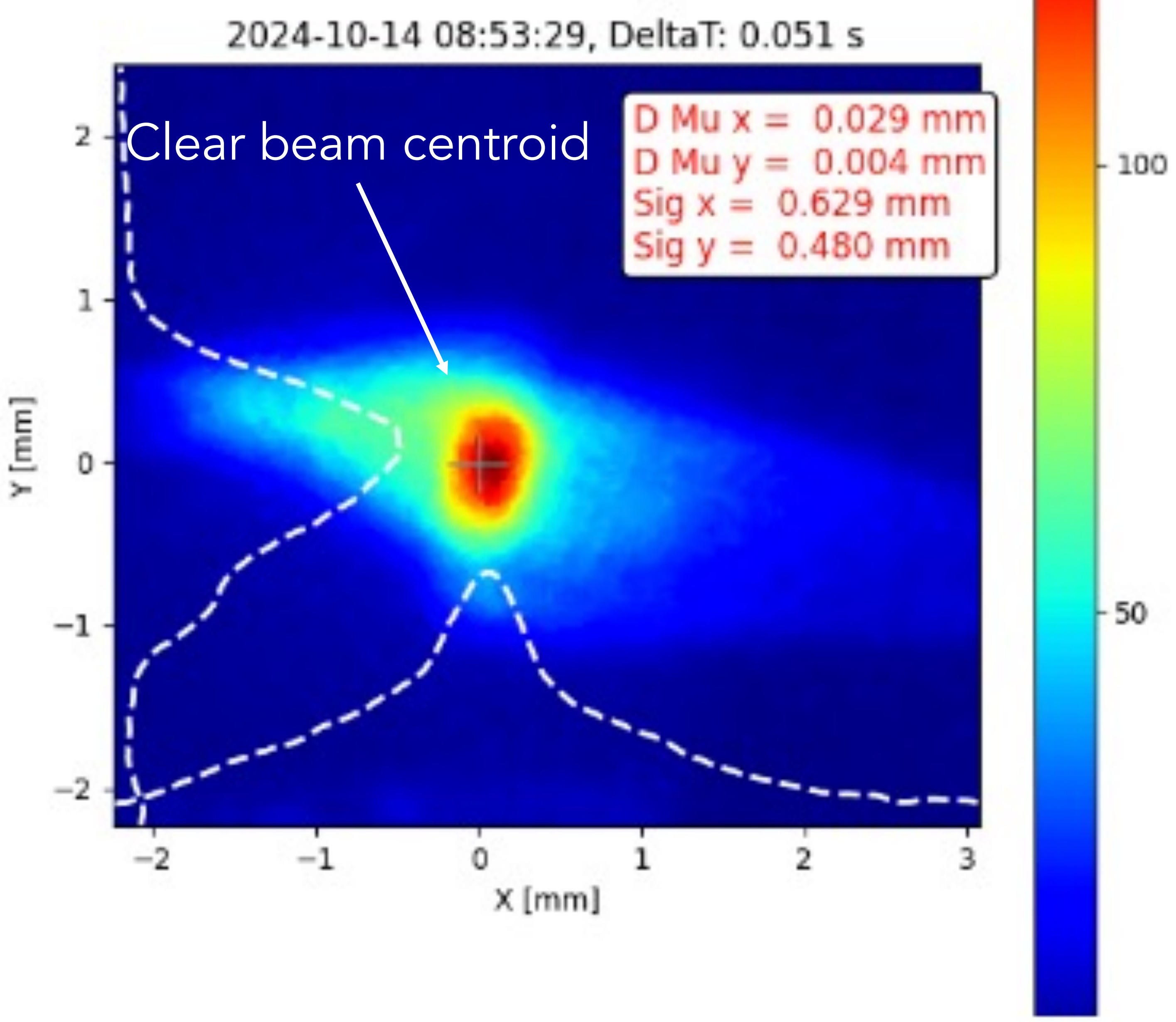
Alignment tolerance << c/w_{pe} ~ 0.3-1mm !!

YAG +0.5m



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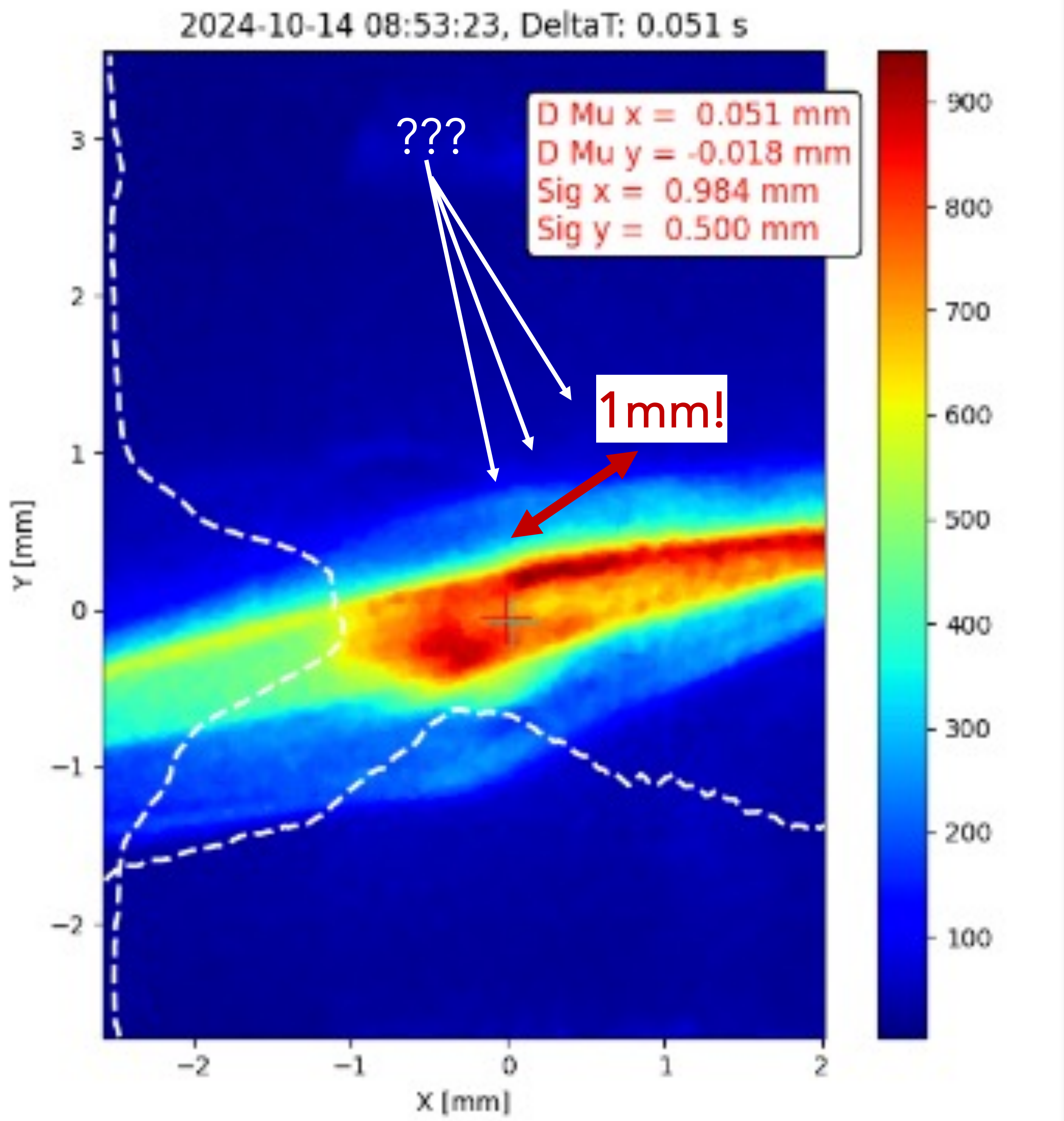
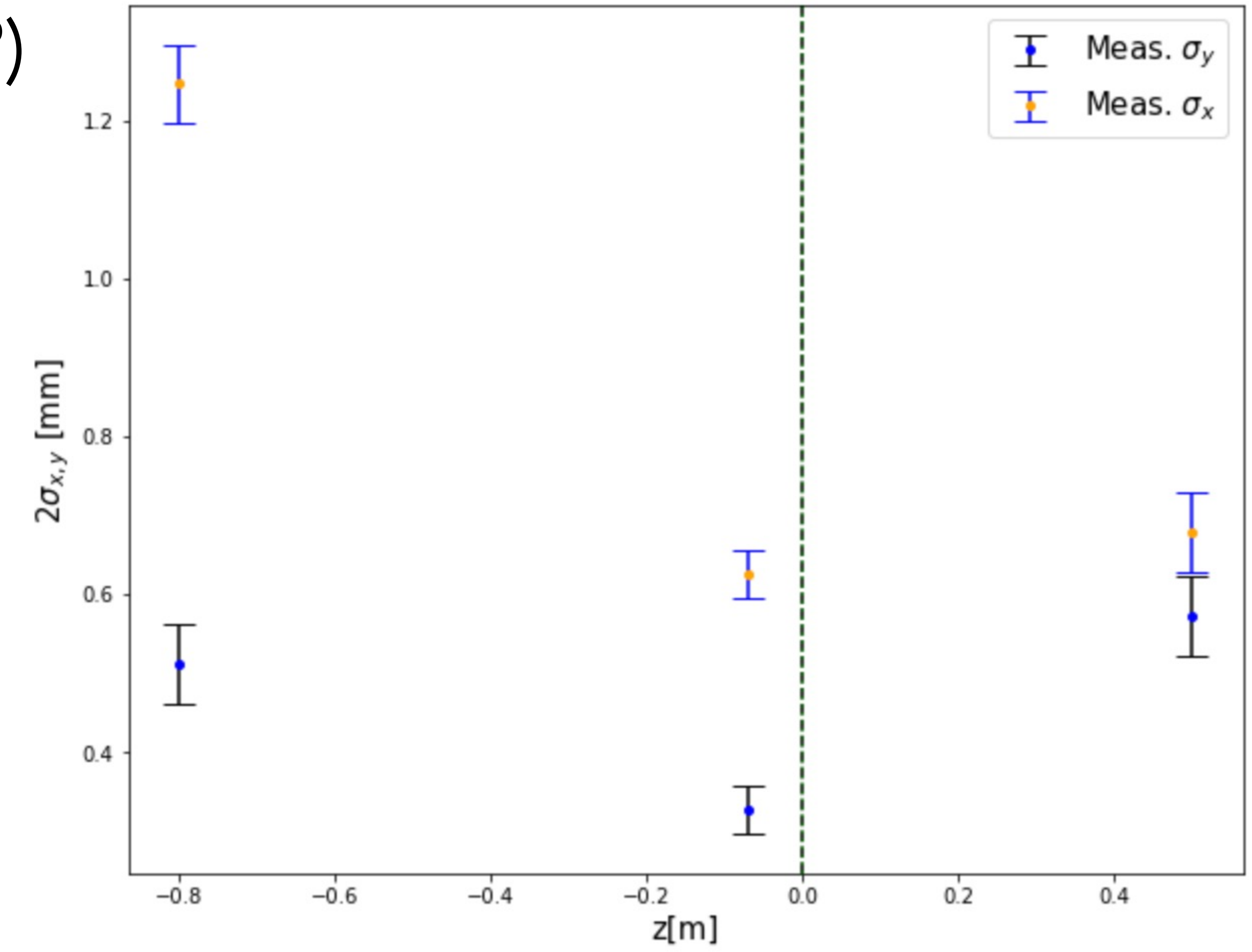


YAG -0.8m

YAG -0.08m

YAG +0.5m



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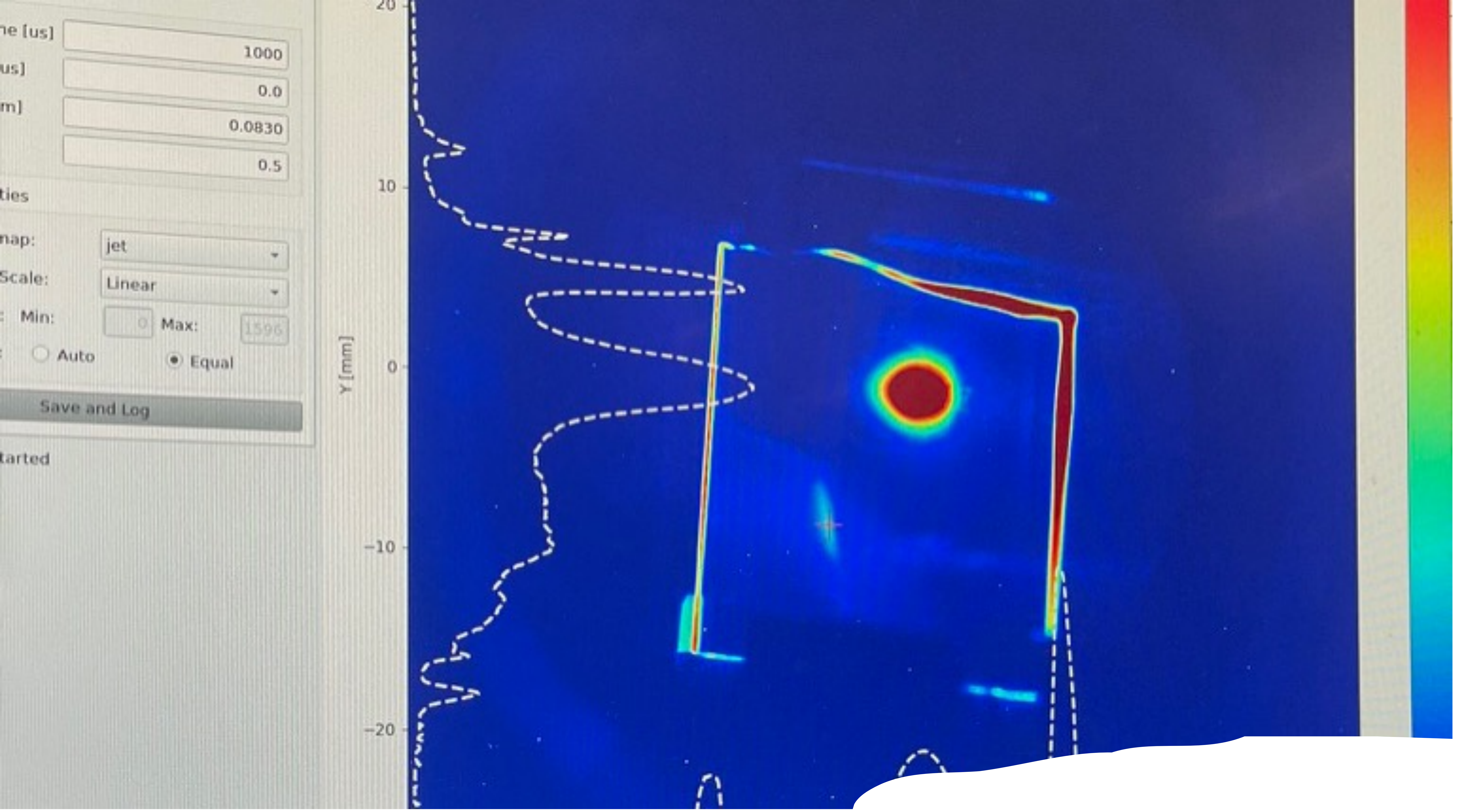

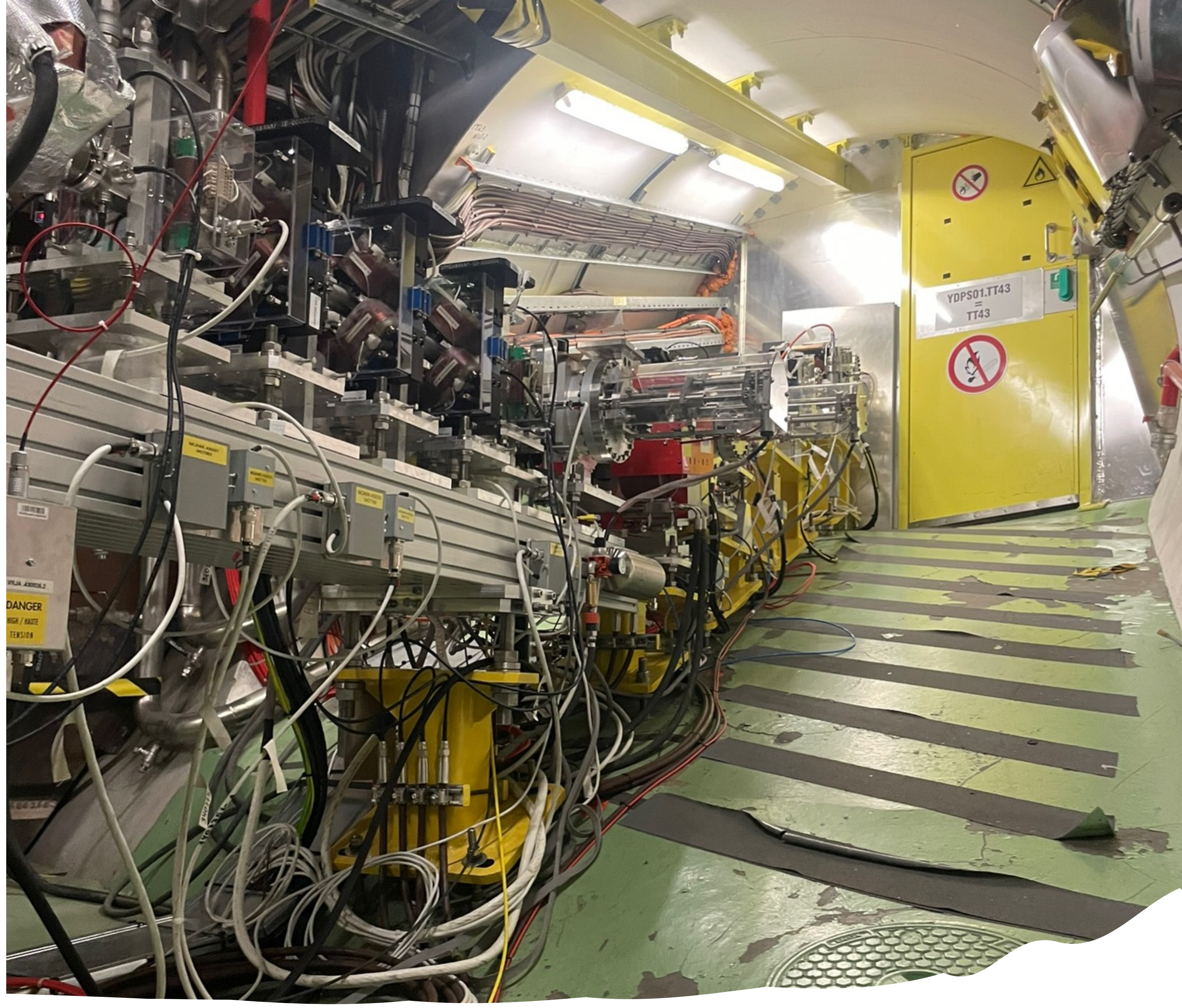

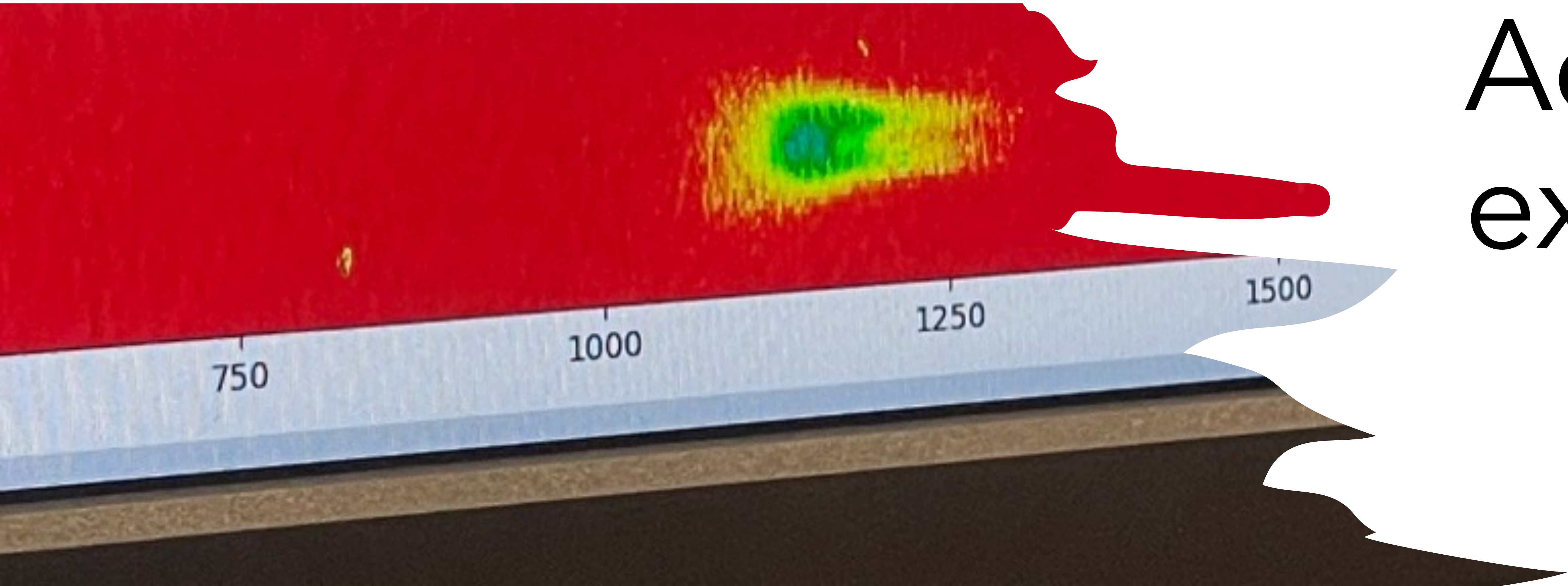

Acceleration experiments

External off-axis injection of witness particles

External injection ? → relatively low amplitude wakefields (~0.5 GV/m) of high phase velocity (relativistic factor $\boldsymbol{\gamma} \sim \boldsymbol{\gamma}_{p+} \sim 427$)

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Off axis injection ? → and several meters into the vapour source at a position (ze ~ 1–6m), to avoid the loss of witness particles due to wakefield phase shifts occurring during SM or from the density step → **this requires flexibility of the setup to be able to focus the beam meterwise along the vapour source**

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Electron witness beam setups used for acceleration experiments (2024)

Two most common configurations

Site of injection is set to be == focal point of electron bunch

Beam waist at 1.5m

Charge: 400pC or 800pC
Max injection angle ~7mrad

Beam waist at 5.5m

Charge: 400pC or 800pC
Max injection angle ~1.2mrad

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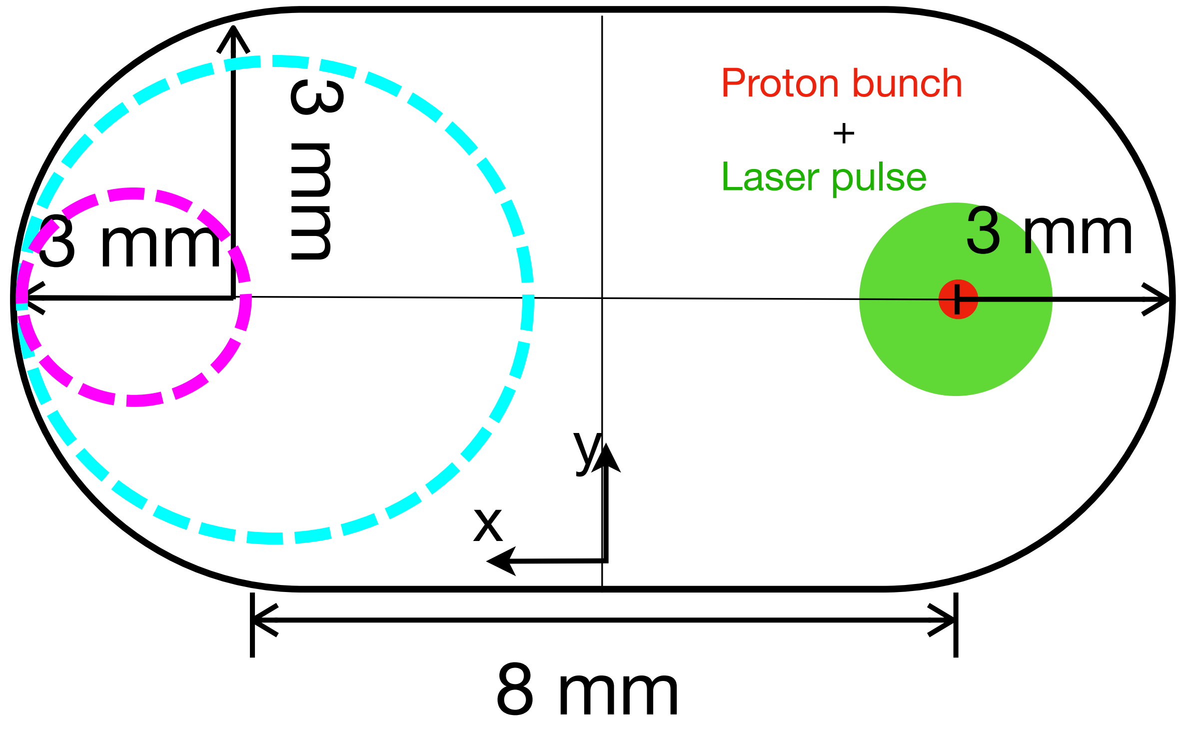
Maximum injection angle without significant beam losses at the entrance aperture



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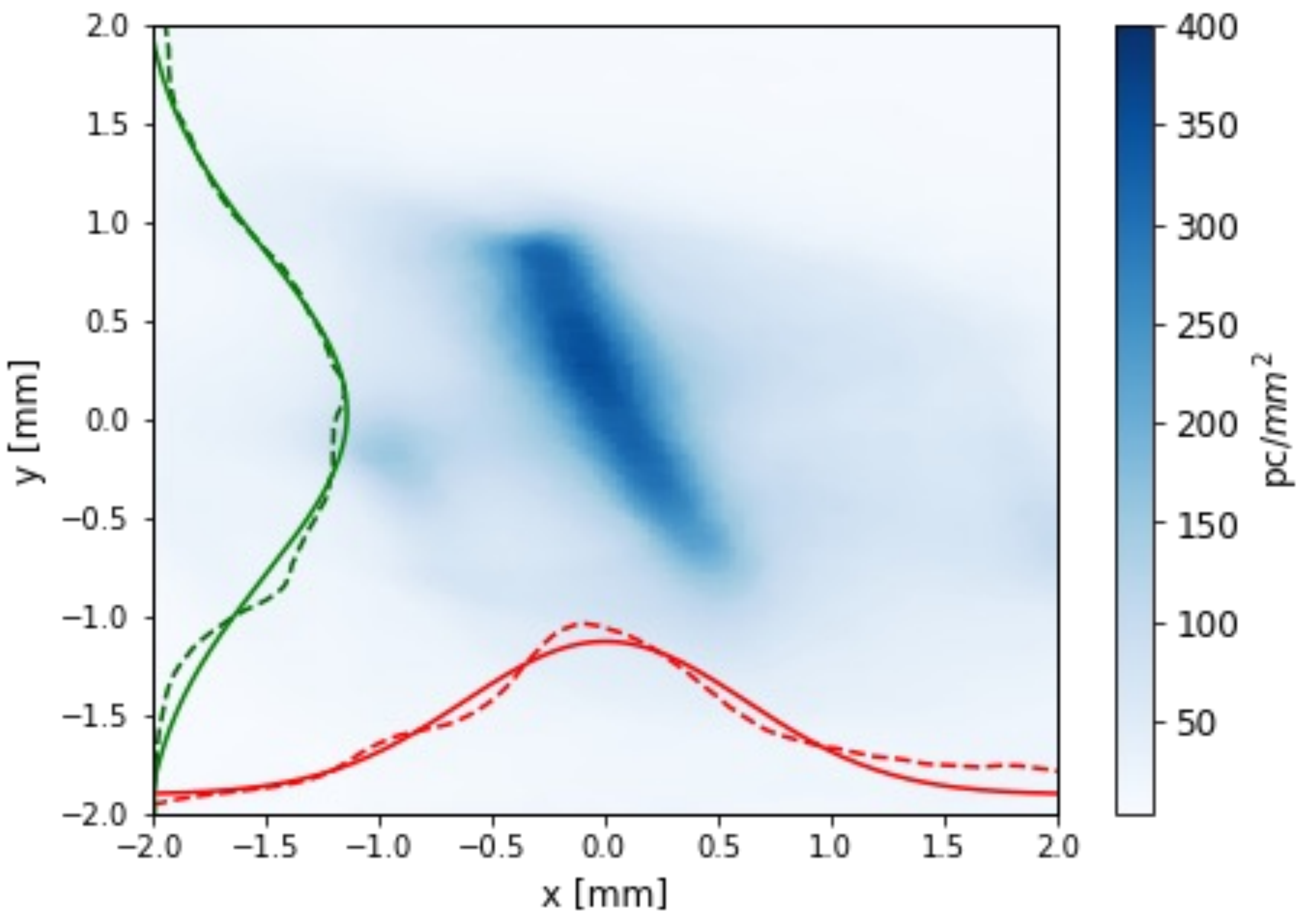
Measurement on
YAG +1.5m

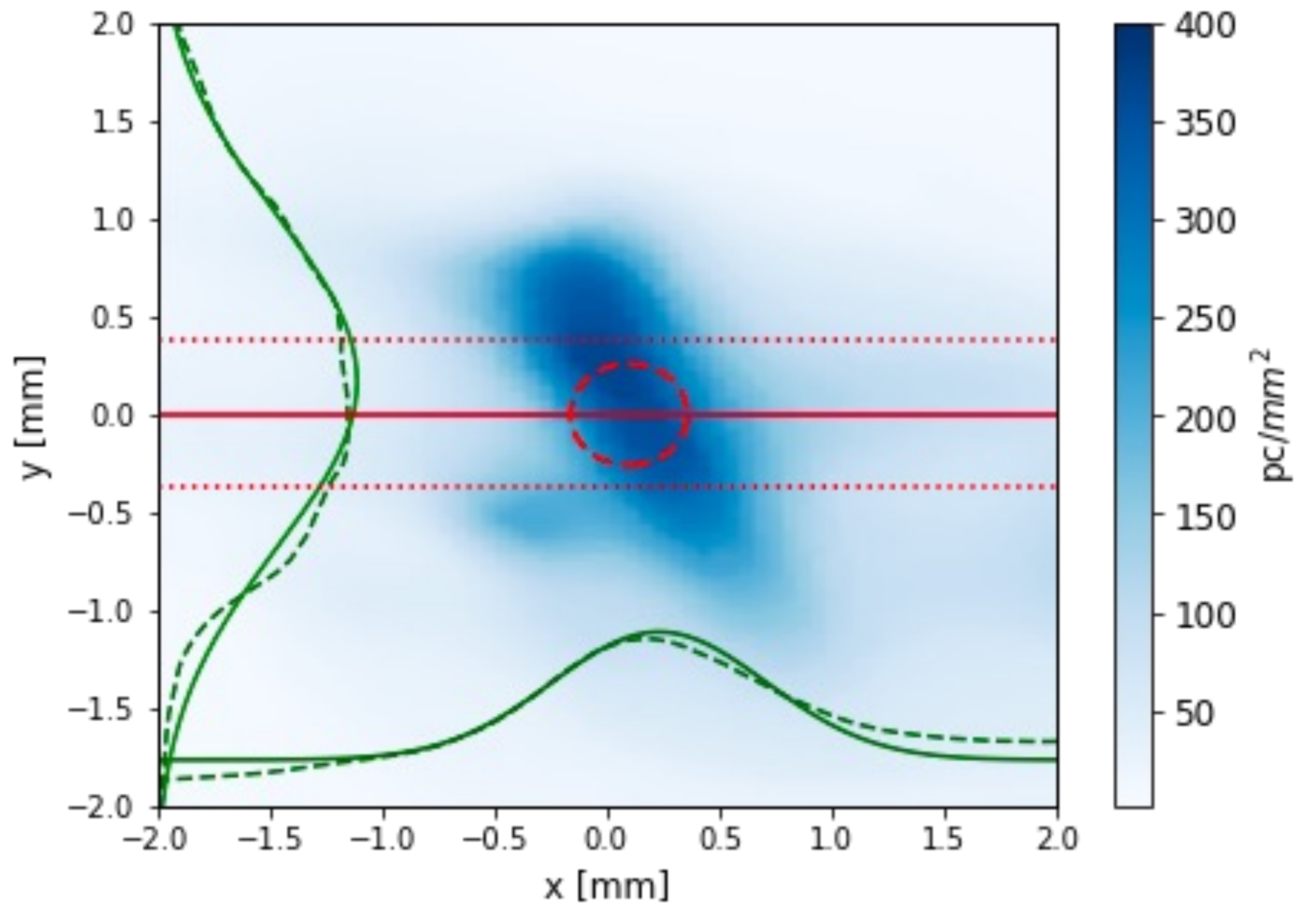


Site of injection is set to be == focal point of electron bunch

Beam waist at 5.5 m

Charge: 400 pC
Injection angle ~1.2 mrad

Measurement on
YAG +5.5m



Dashed horizontal lines: plasma skindepth
for plasma electron density of 2e14
Red circle: proton bunch 1σ contour

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Measurement of the electron beam waist location

Beam waist at 1.5m

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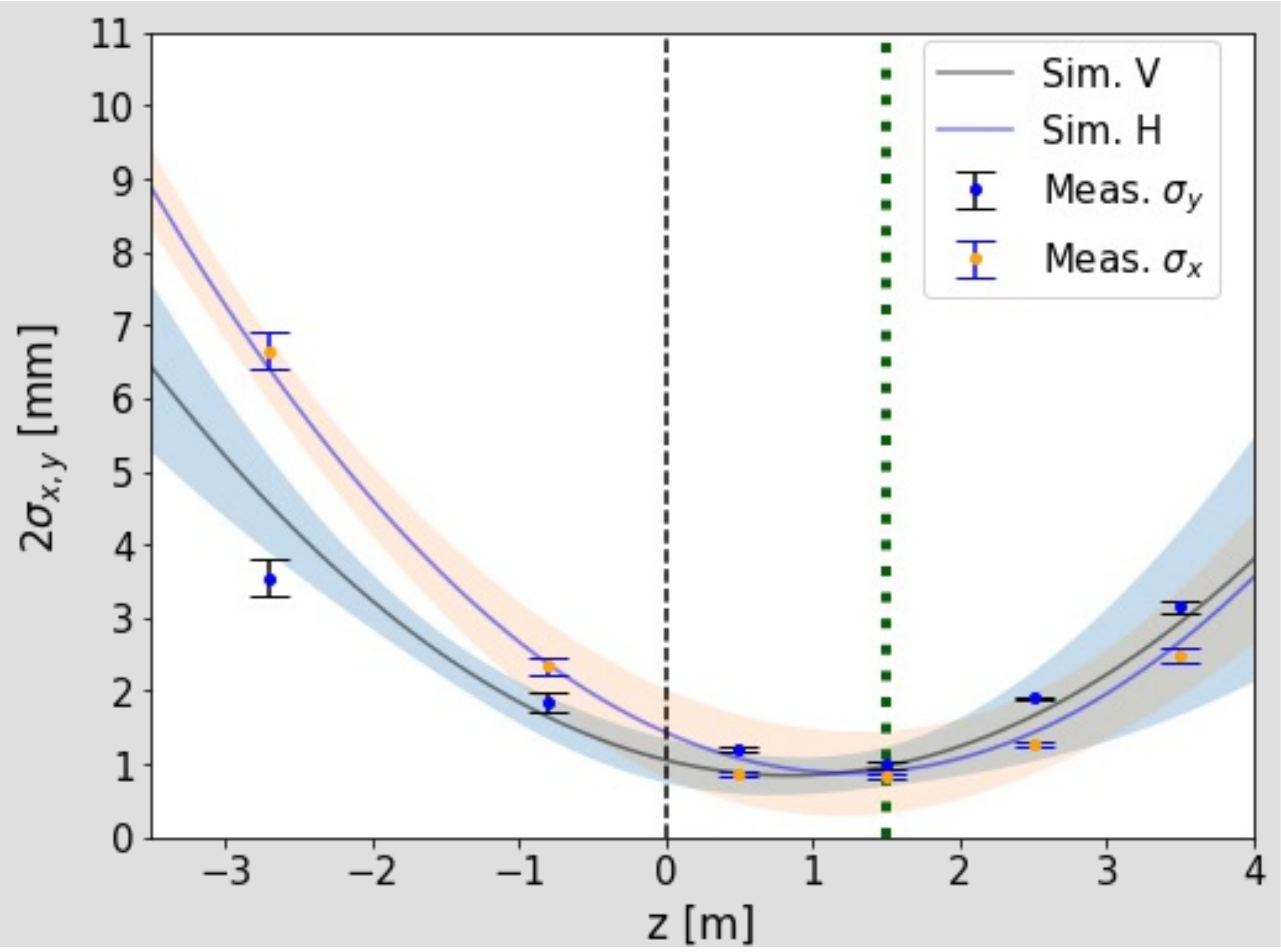

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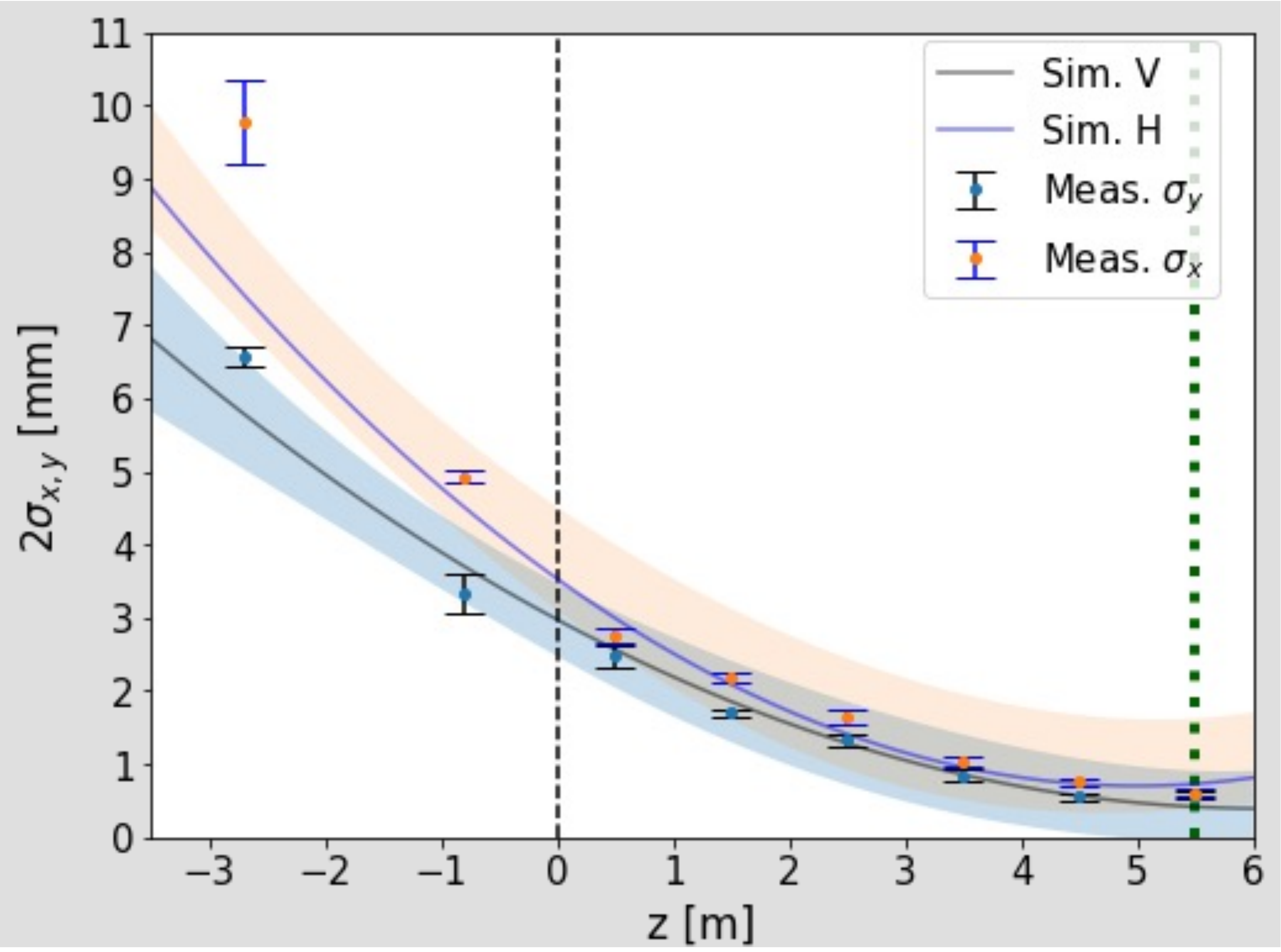

Measurement of the electron beam waist location

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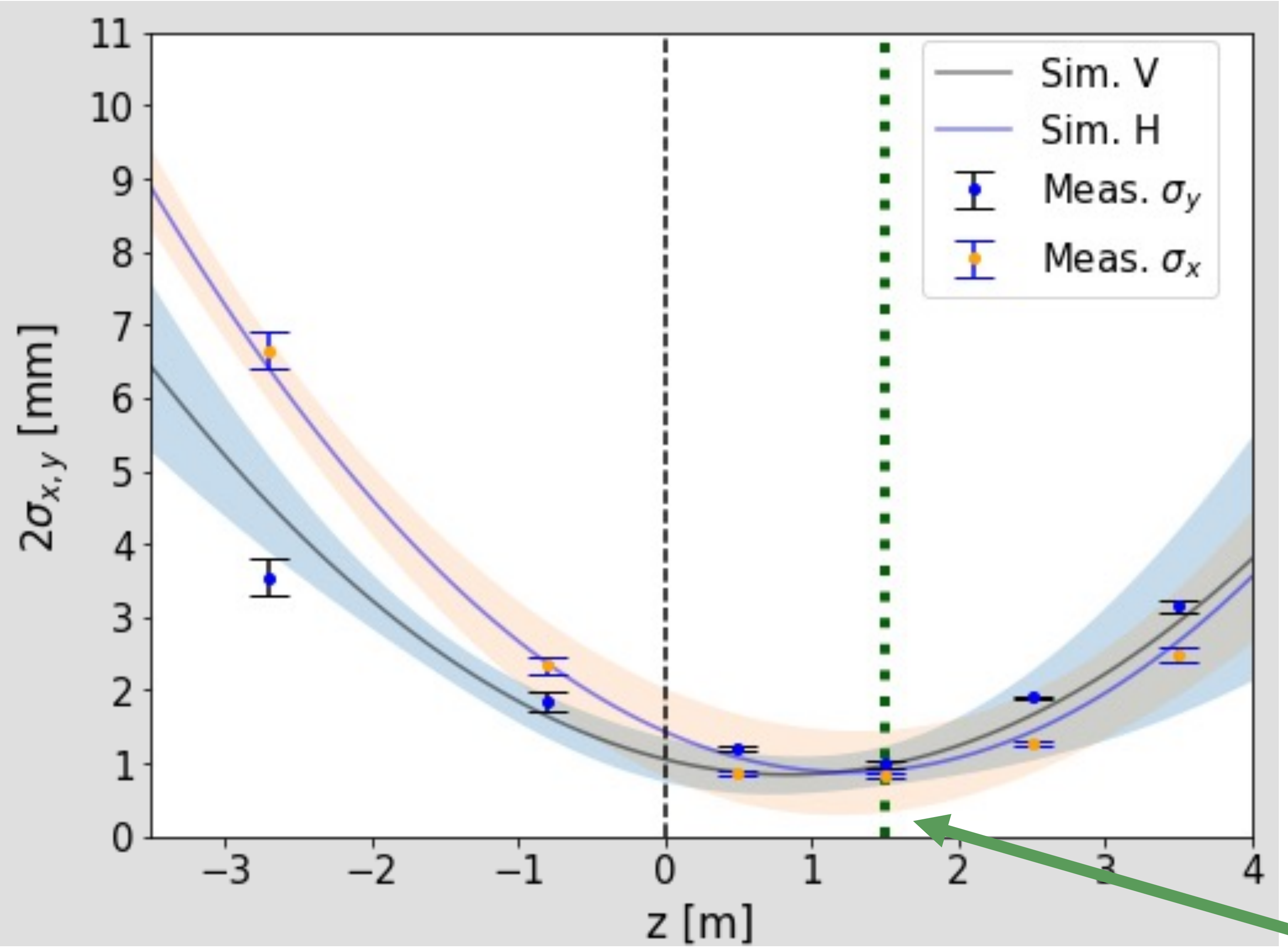

Injection location

Beam waist at 5.5m

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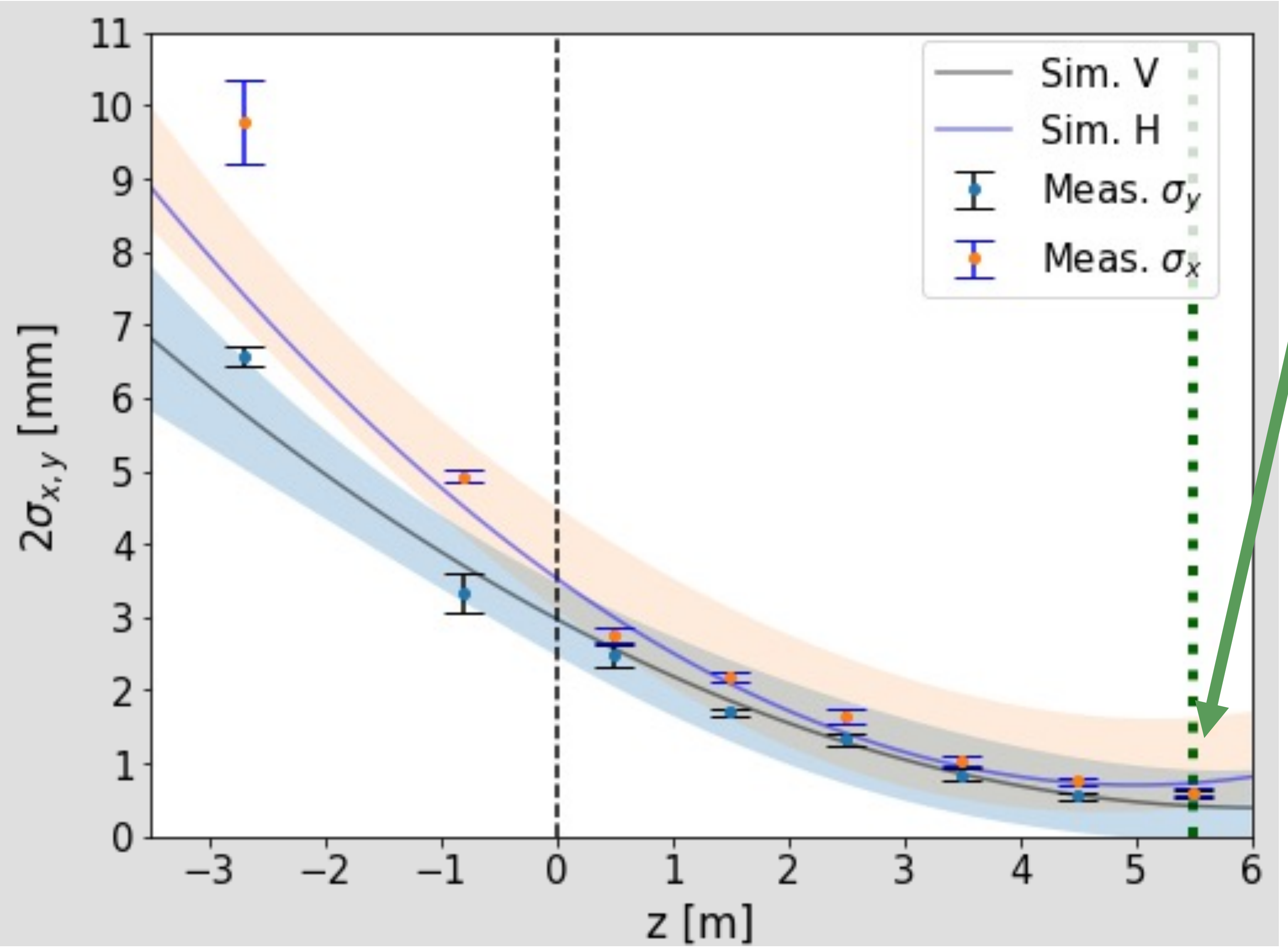

- Good agreement between measurements and simulation results
- Waist location within 1m of injection position (β*~ 0.5m)

Electron beam centroid position jitter at focus
(for 400 pC and 800 pC bunches used in acceleration experiments)

Beam centroid and sizes calculated using Gaussian fits to the hor. / ver. projections

Beam waist at 1.5m

For 400 pC <90 μm with a beam size of 500/420 μm
For 800 pC <105 μm with a beam size of 690/770 μm

Focus	Charge [pC]	Sig_x [mm]	Sig_y [mm]	Centroid jitter [mm]
1.5m	200	0.441± 0.023	0.349 ± 0.017	(0.051, 0.042)
1.5m	400	0.498 ± 0.022	0.418 ± 0.047	(0.090, 0.075)
1.5m	800	0.687 ± 0.045	0.768 ± 0.058	(0.102, 0.097)

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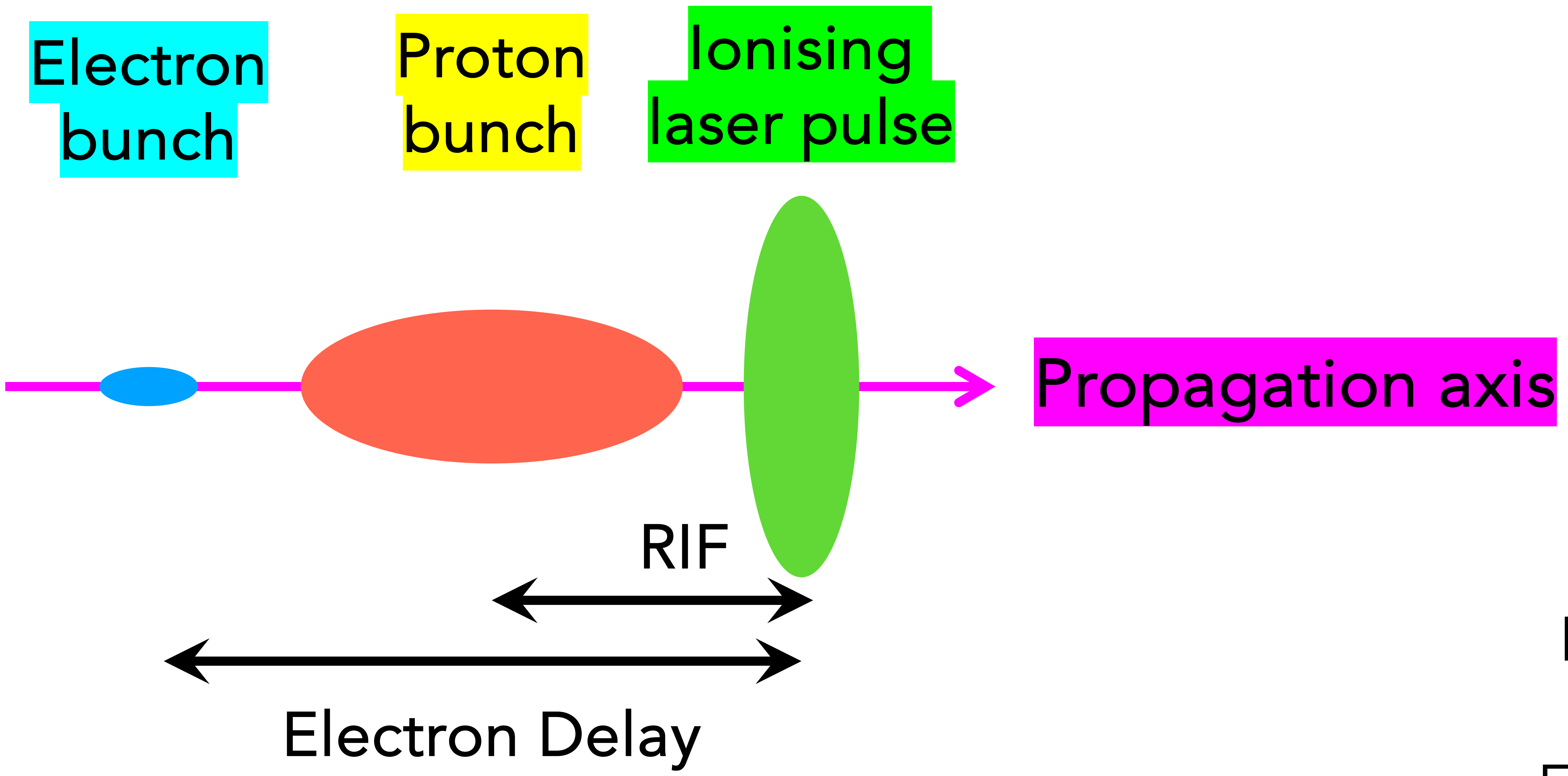
Conclusion: electron beam position jitter smaller than the transverse beam size

Adjusting electron beam timing (w.r.t laser pulse)

- Commonly needed for acceleration studies to investigate the wakefields along the proton bunch. Adjustment range: ~ [50, 600] ps
- For seeding/hosing: close to the laser pulse (~ 0ps)



Proton bunch rms length ~200ps
Electron bunch rms length ~ 2-5ps

Adjusting electron beam timing (w.r.t laser pulse)

- UV pulse is derived from main laser pulse
- RF system and booster structure timing are synched with the main laser pulse

    <=> Change electron beam delay

    <=> Delay UV pulse on cathode

    <=> Adjust RF phase to compensate

=> These adjustments may change the electron beam alignment

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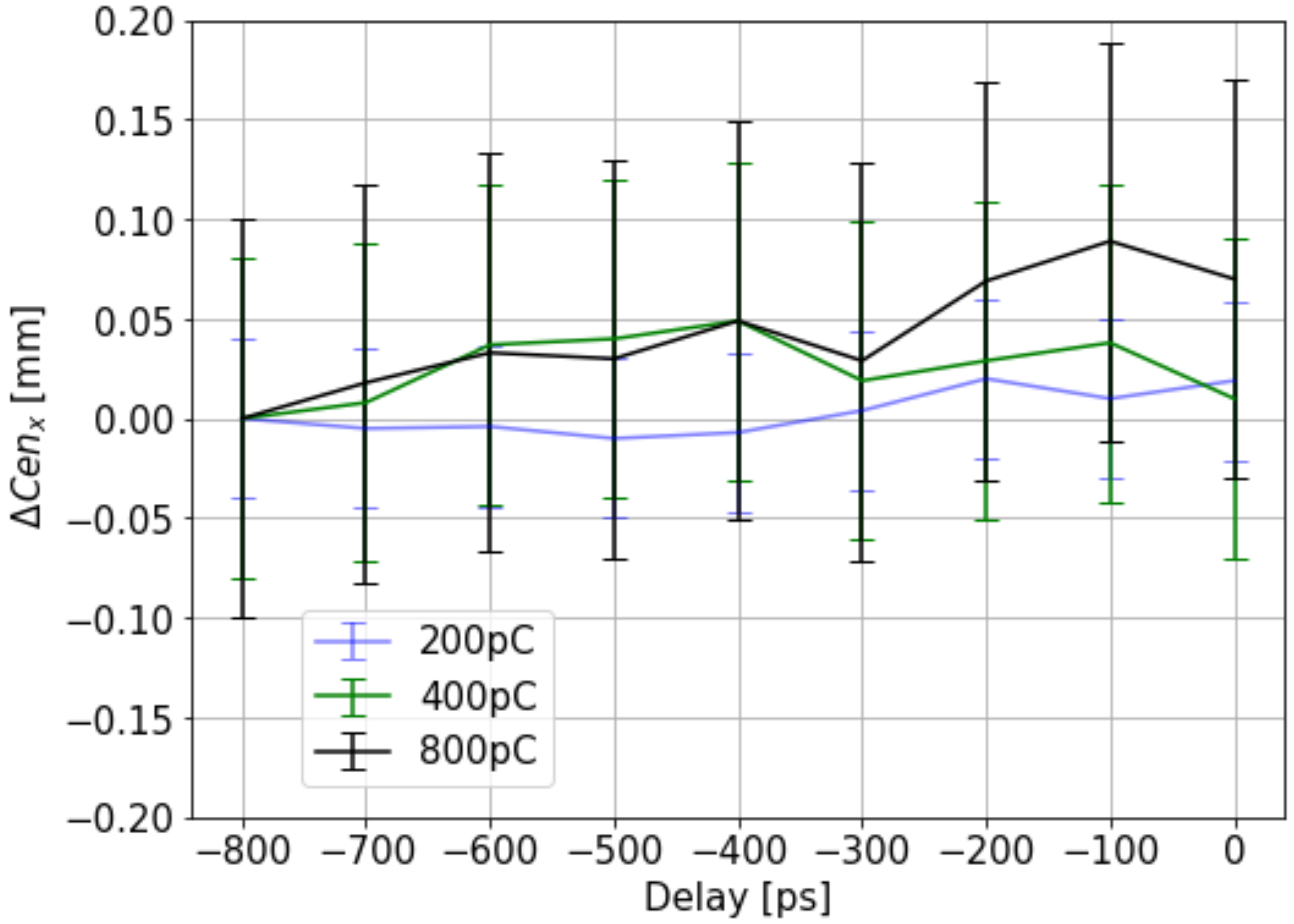
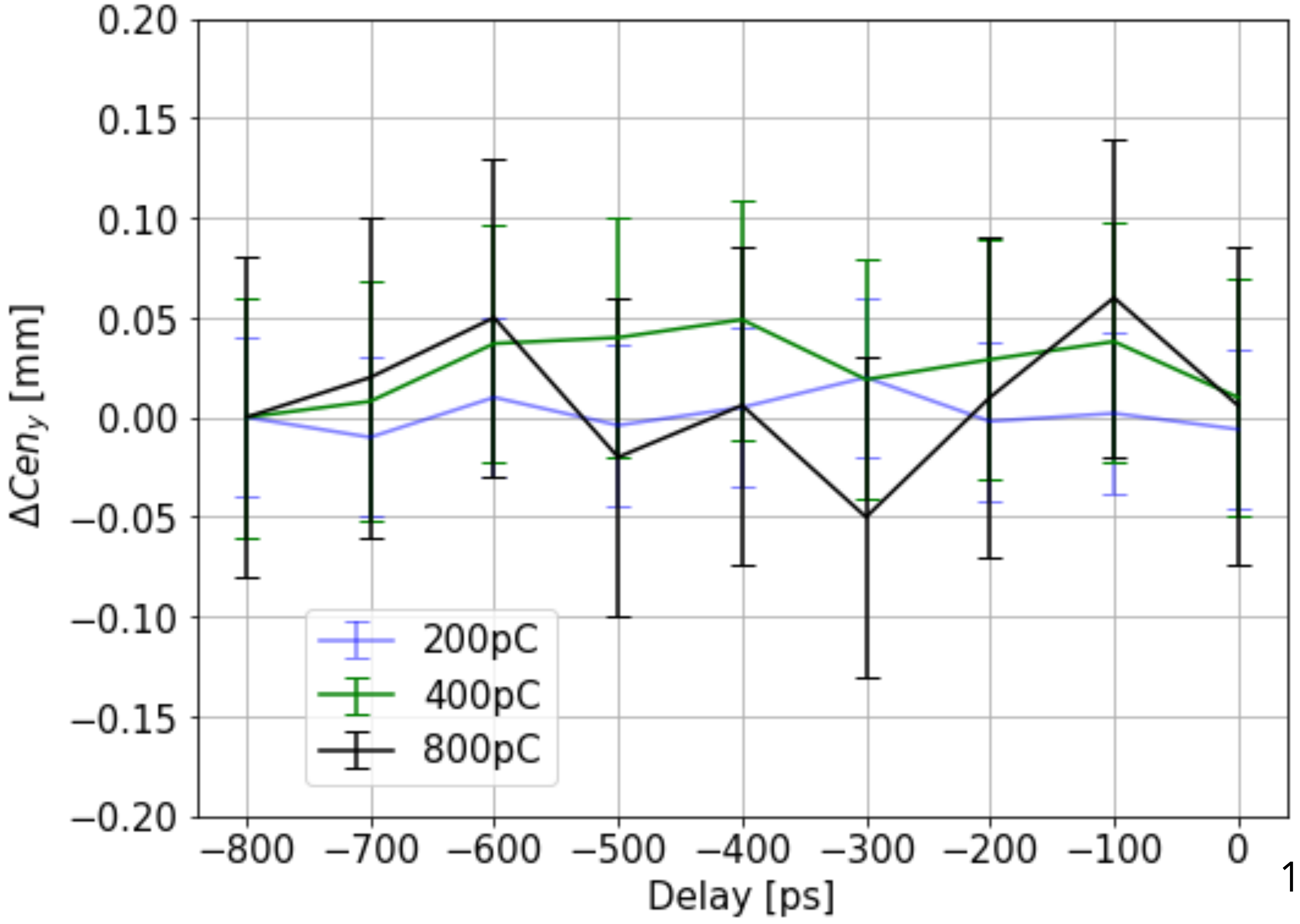
- Centroid position shifts < centroid position jitters for all cases





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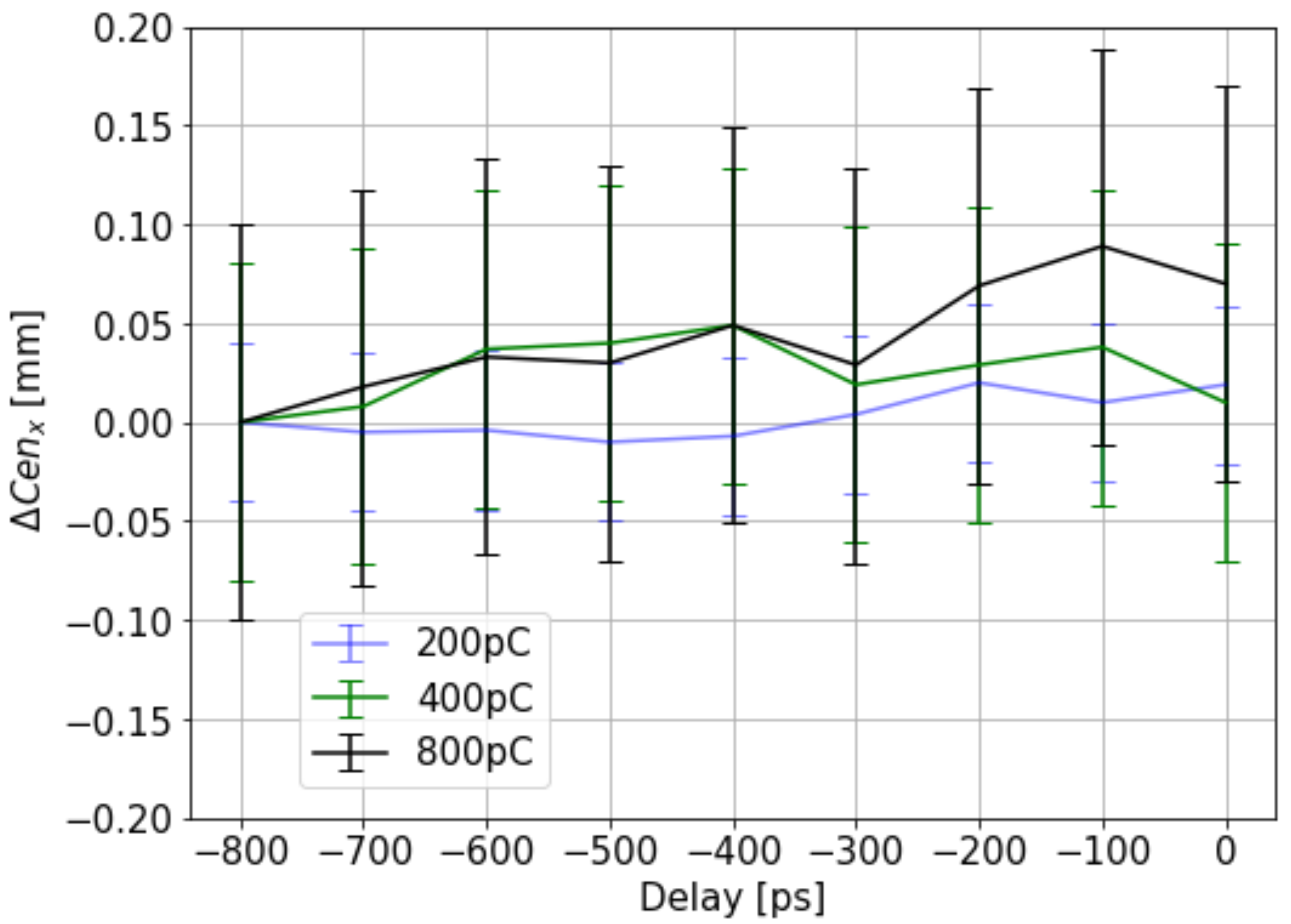
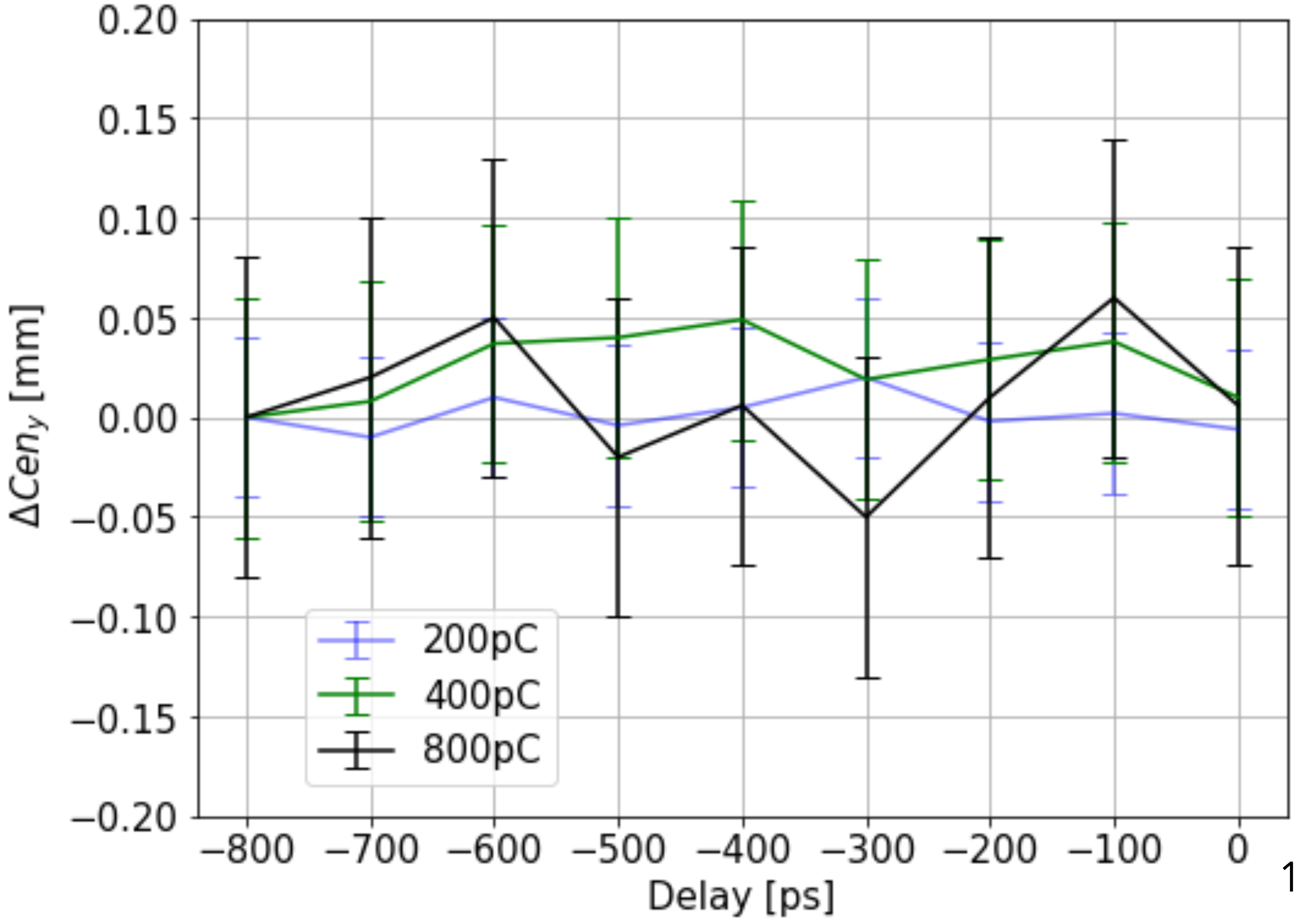
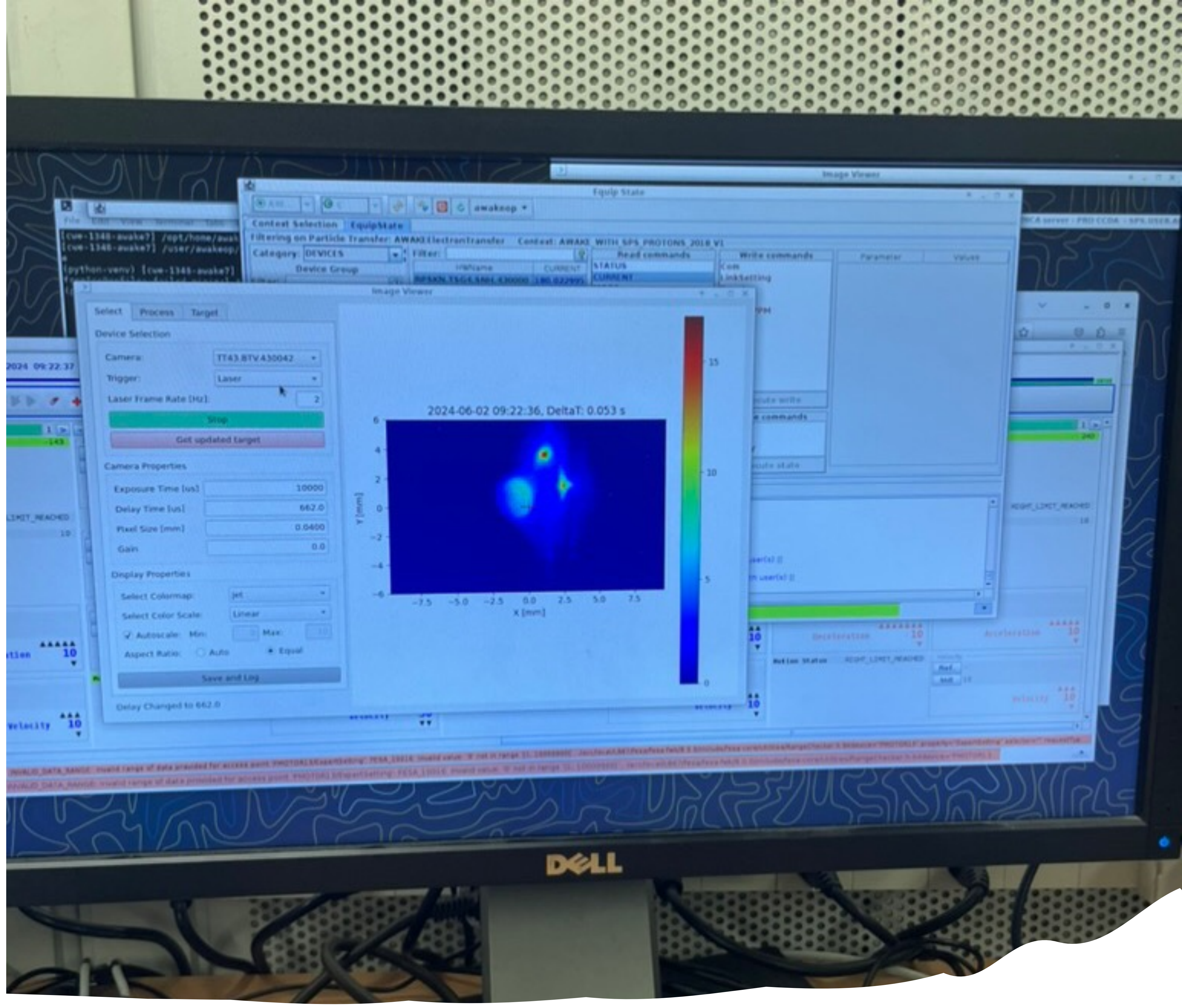
→ Conclusion: adjustment of the electron beam timing does not compromise its alignment







Deleterious effects

Deleterious effects (I)

- The current in the *spectrometer* magnets (dipole and quadrupole doublet) are commonly varied during acceleration studies (see Fern's talk)

- It was observed that this directly affects the alignment of the injection beam at the injection location

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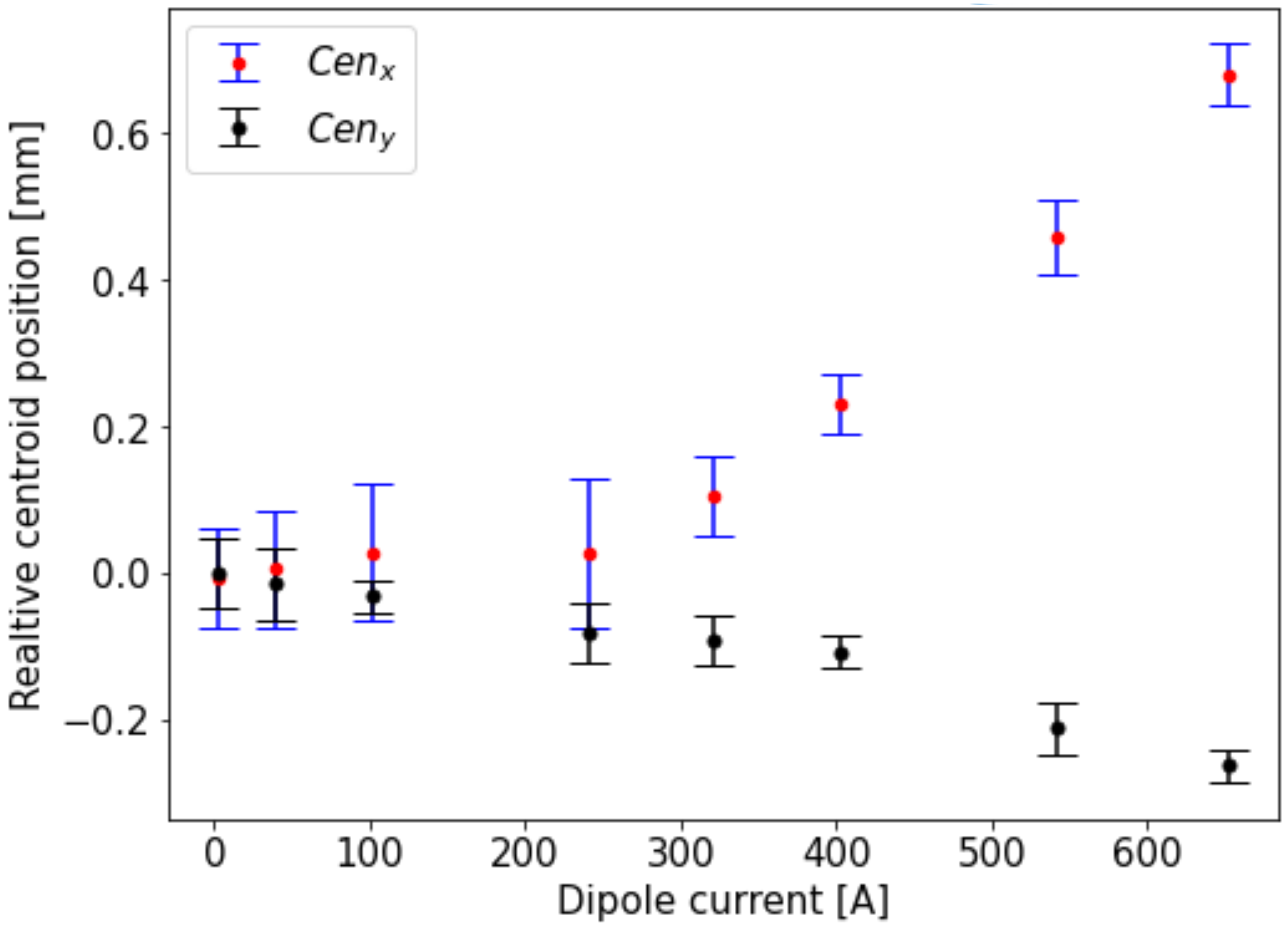
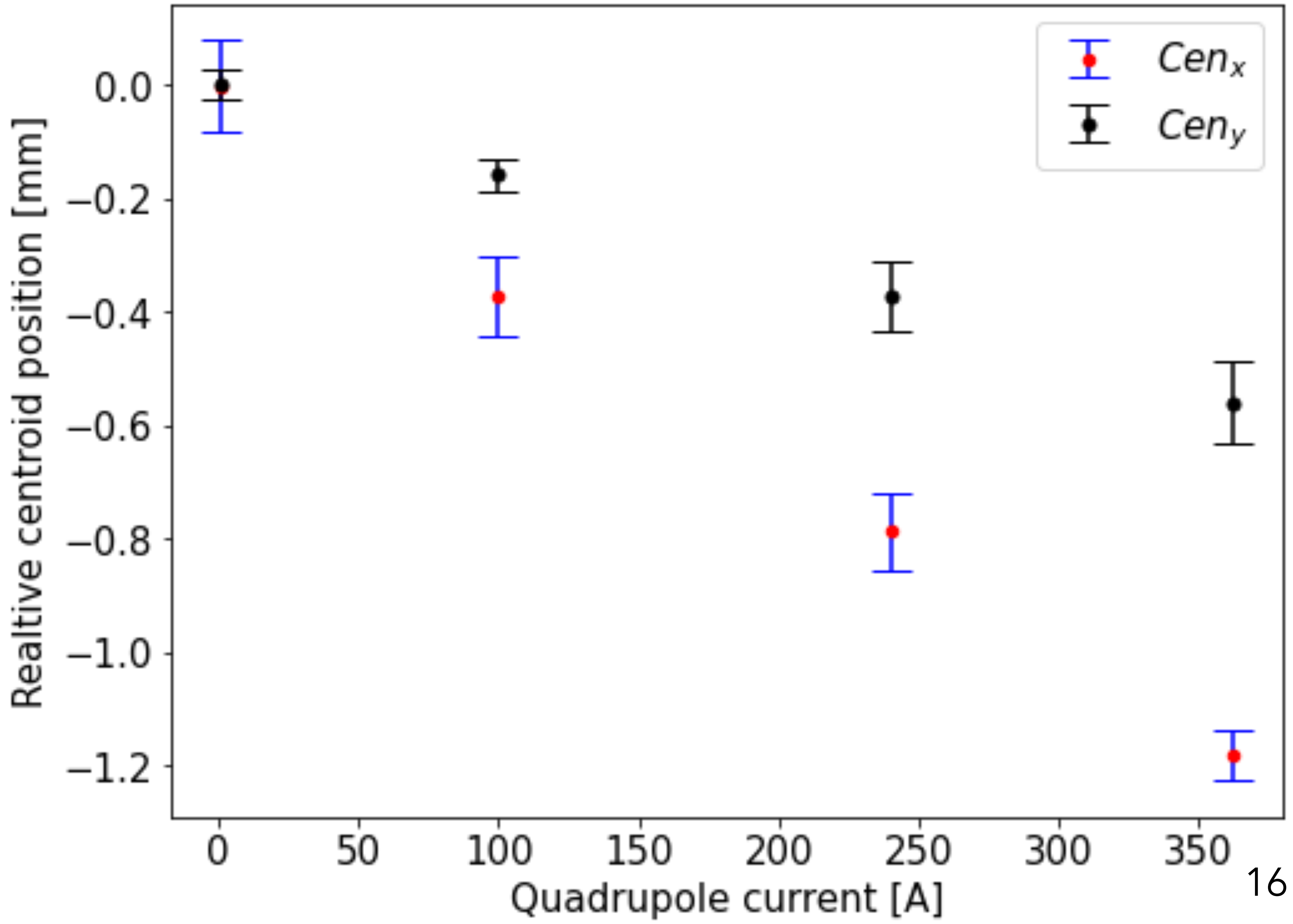
- Measurements (Figures on the RHS) show beam position changes for a 400pC beam, focused at +5.5m. The beam position changes on the mm-scale >> c/w_{pe}!





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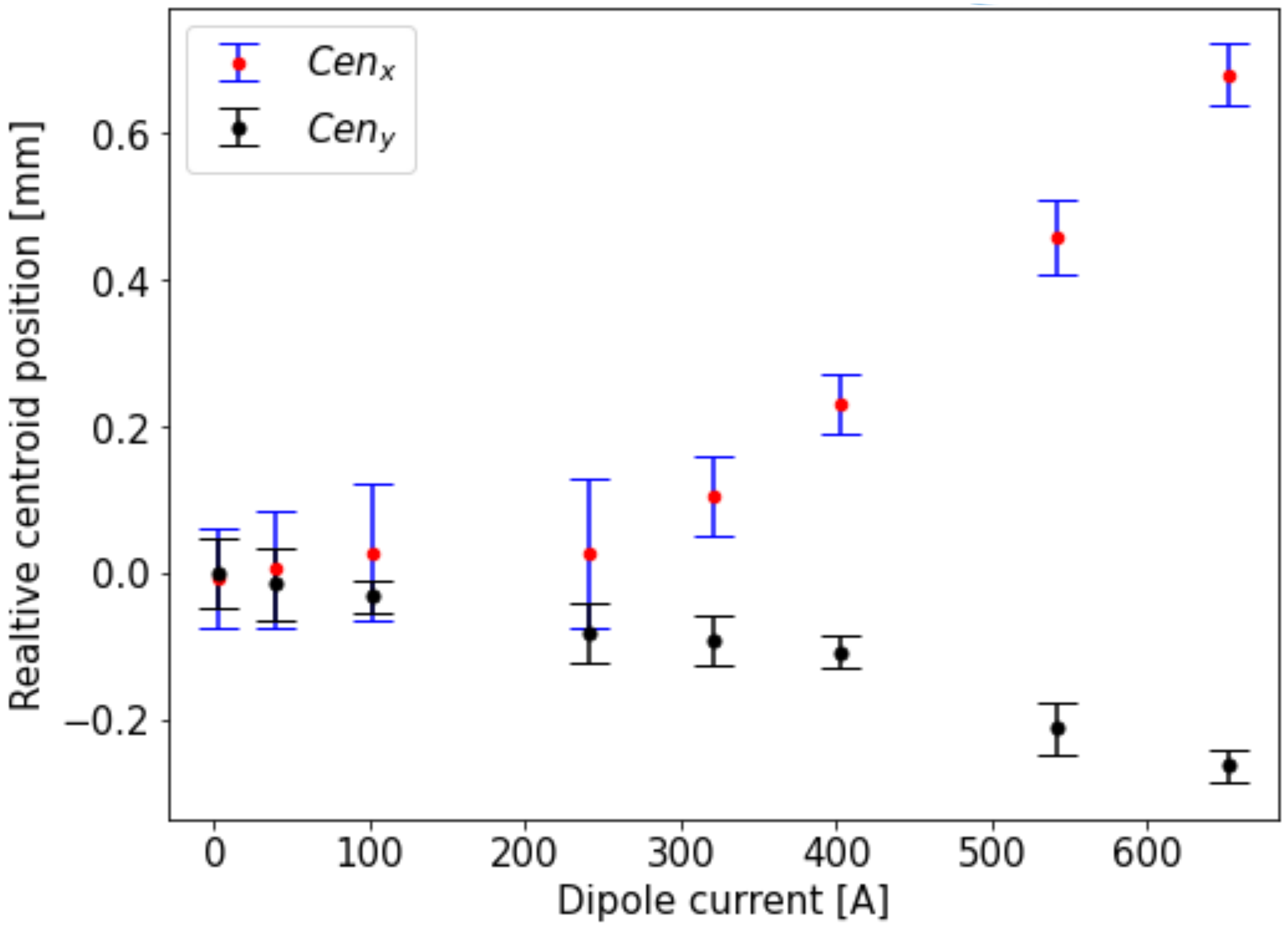
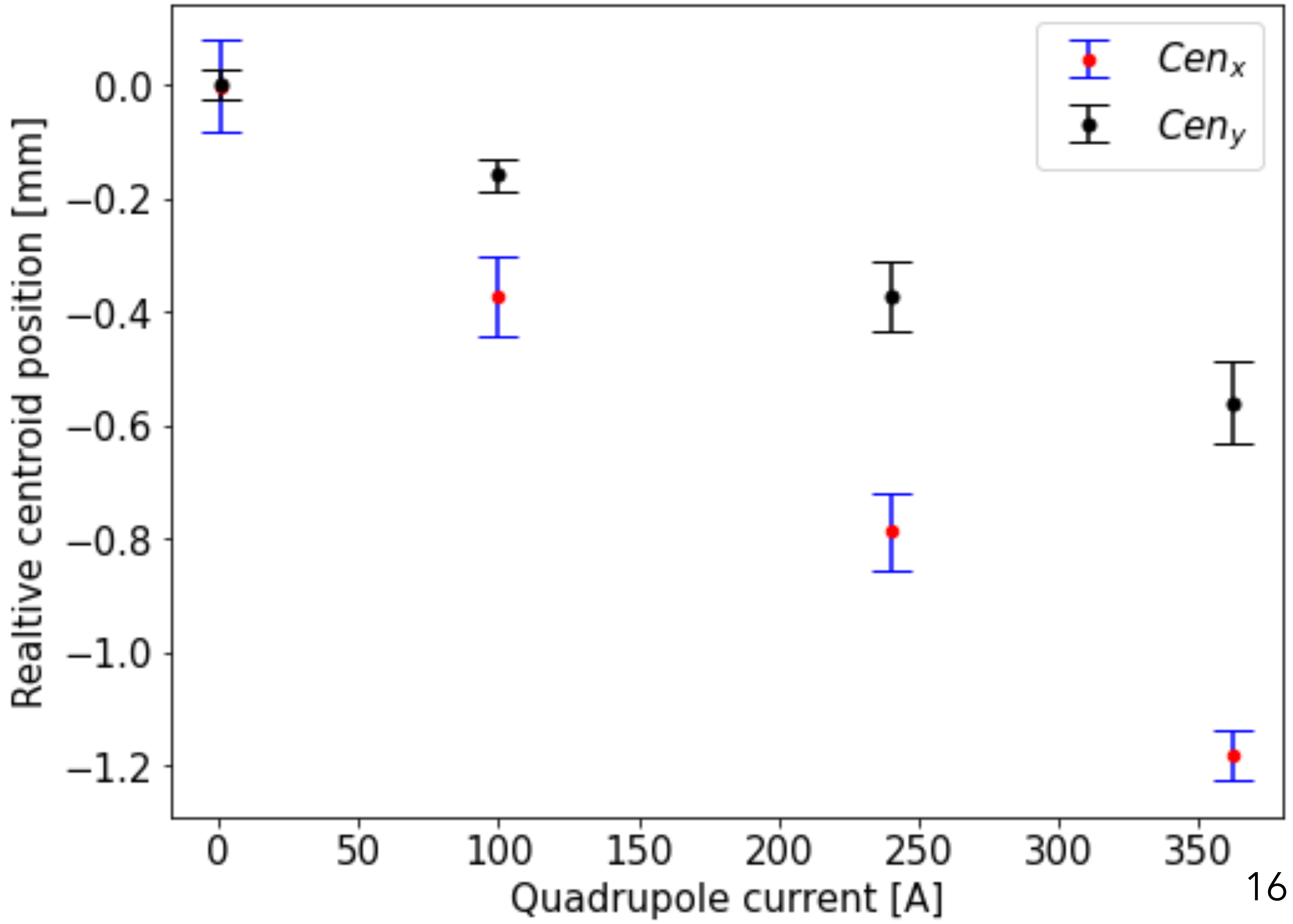
Electron beam alignment is checked after every current change and prior to taking the next measurement





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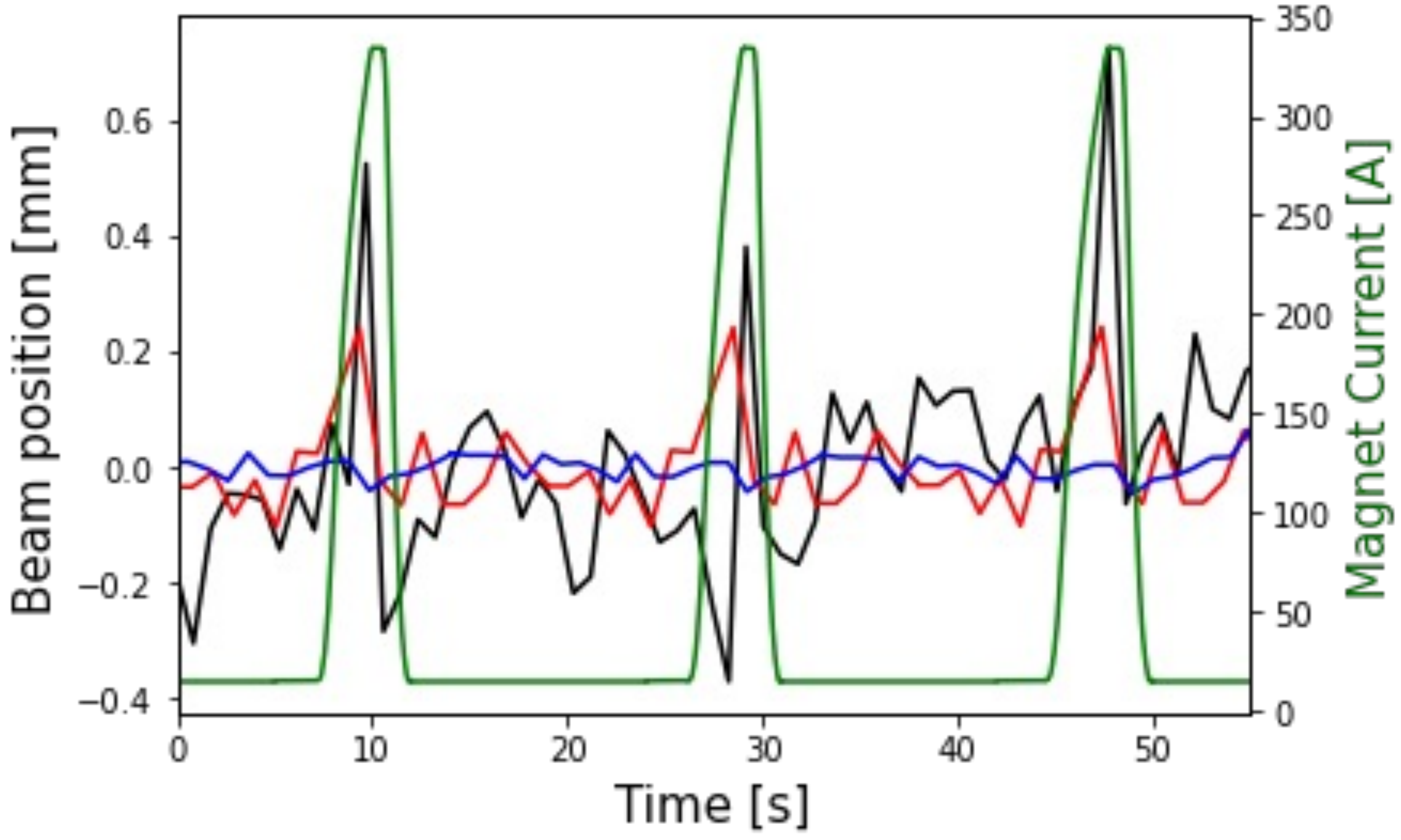
Deleterious effects (II)

- The electron beam position on the BPMs showed significant "jumps" (black line), matching the SPS magnet ramping frequency (~every 20s) (green line)
- This was also observed on the beam screen after the first vertical dispersive element of the line (of lower magnitude (red line)
- At the focal point (here on the screen 5.5m into the vapour source) these jumps are within beam centroid jitters (blue line)



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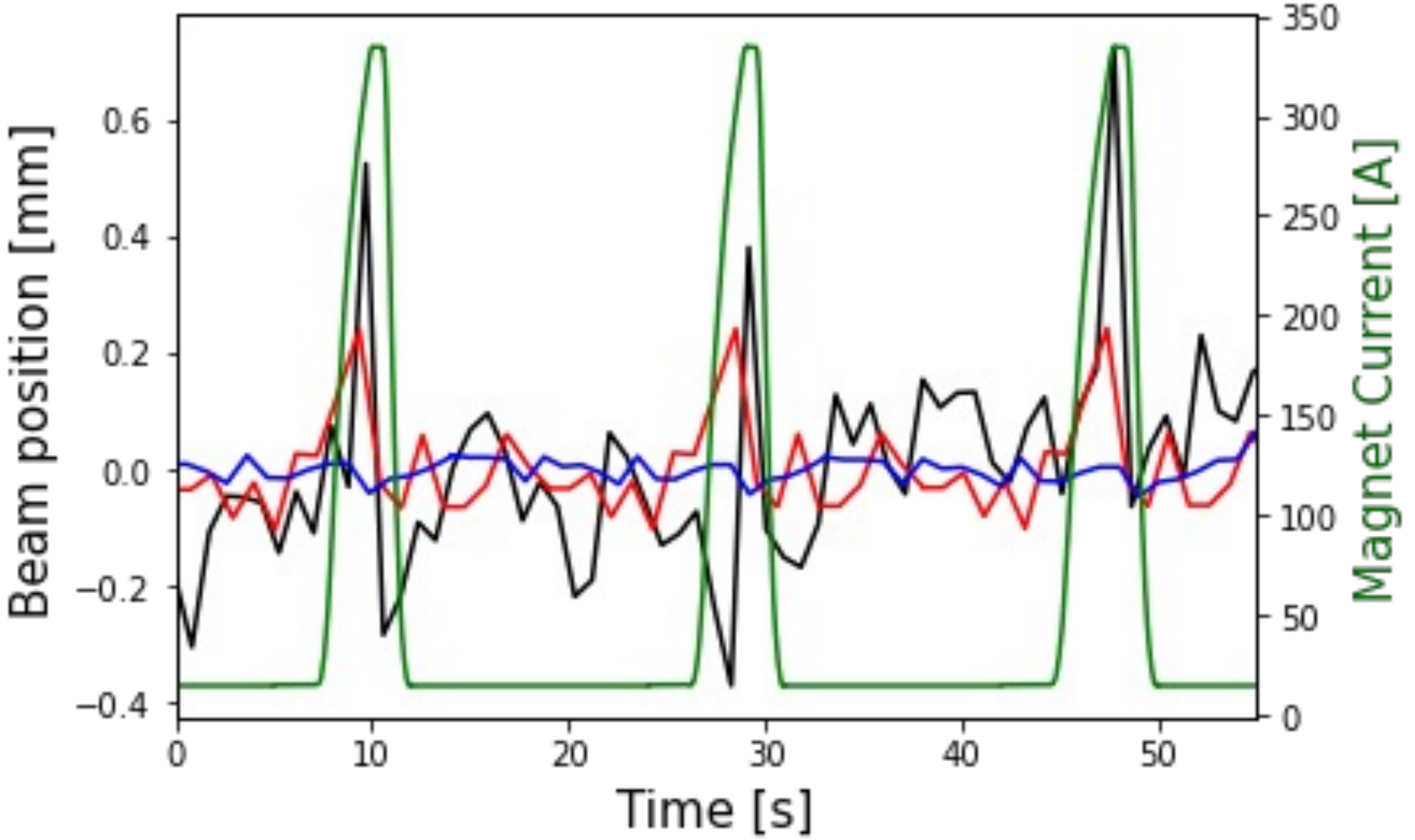
- Most of the time this effect was not observed at the injection location.
- If they were observed → alignment performed with extraction events only.



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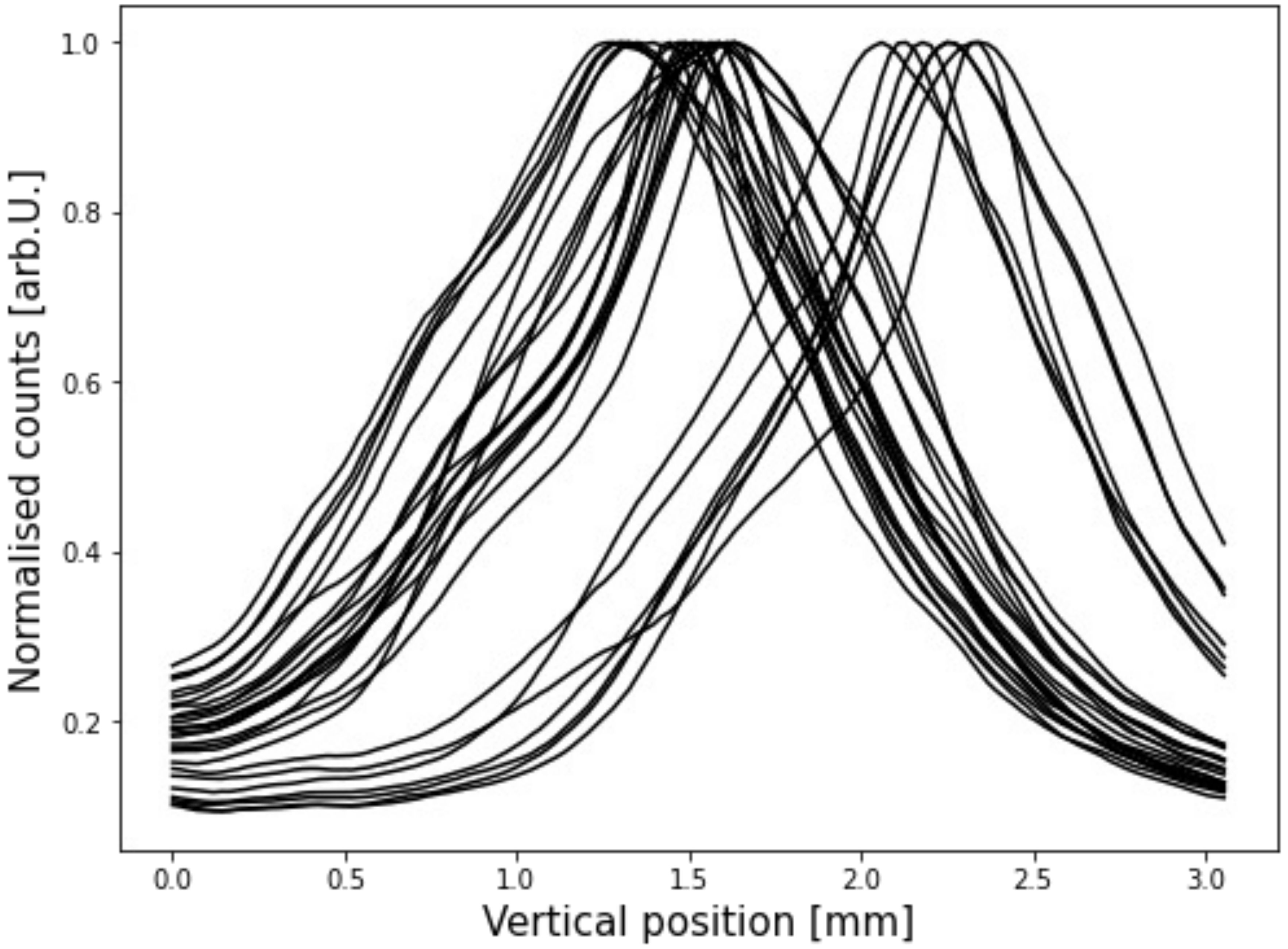
Deleterious effects (thrice)

- During SPS extraction, the electron beam position was observed to shift by several millimetres.
- Some vapor source heaters remained on during extraction, though they should be off before beam arrival. This issue was resolved by adjusting the trigger timing, that turns the heaters off.

Before

Centroid jumps of ~ 1.5mm!



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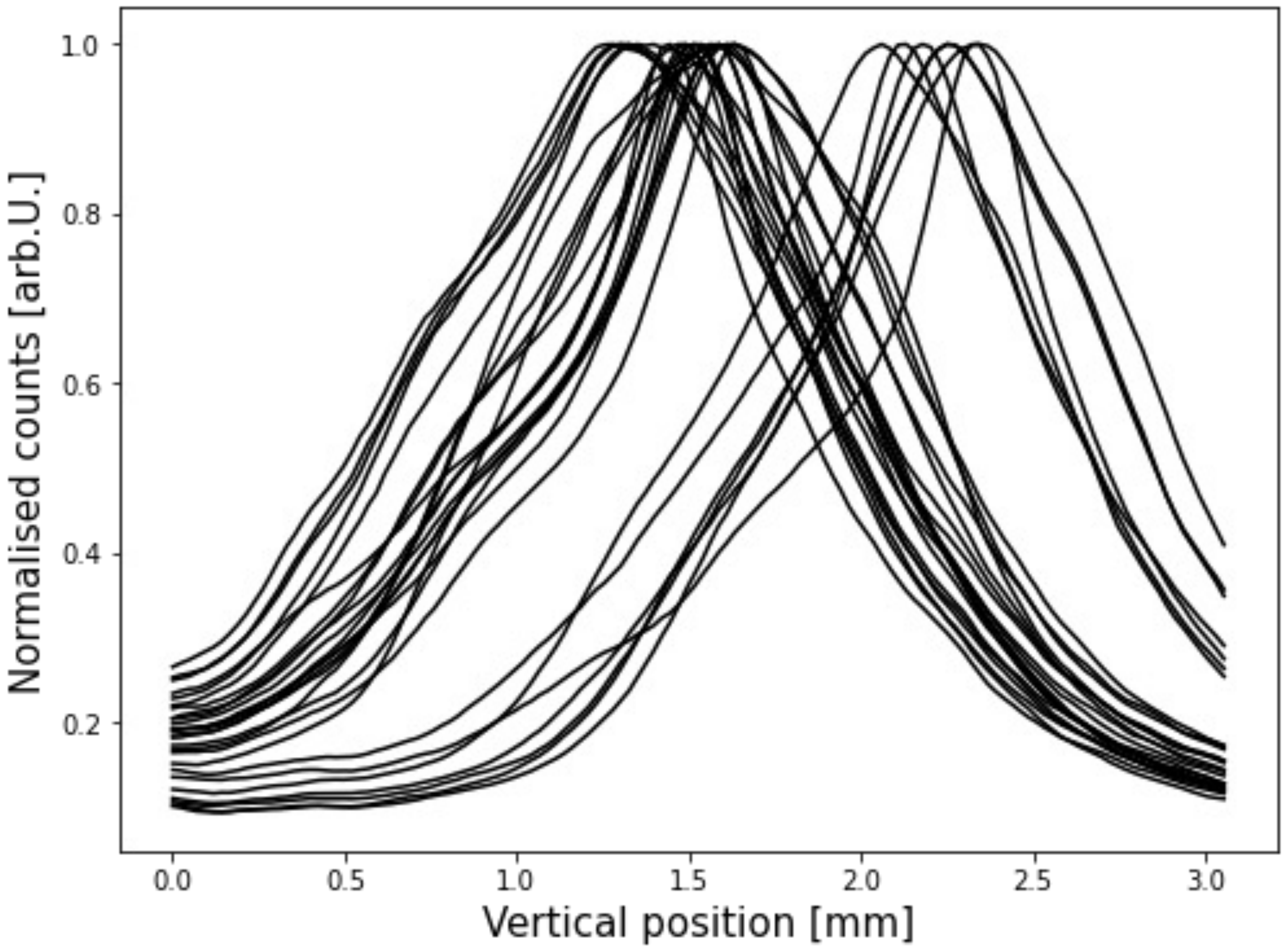
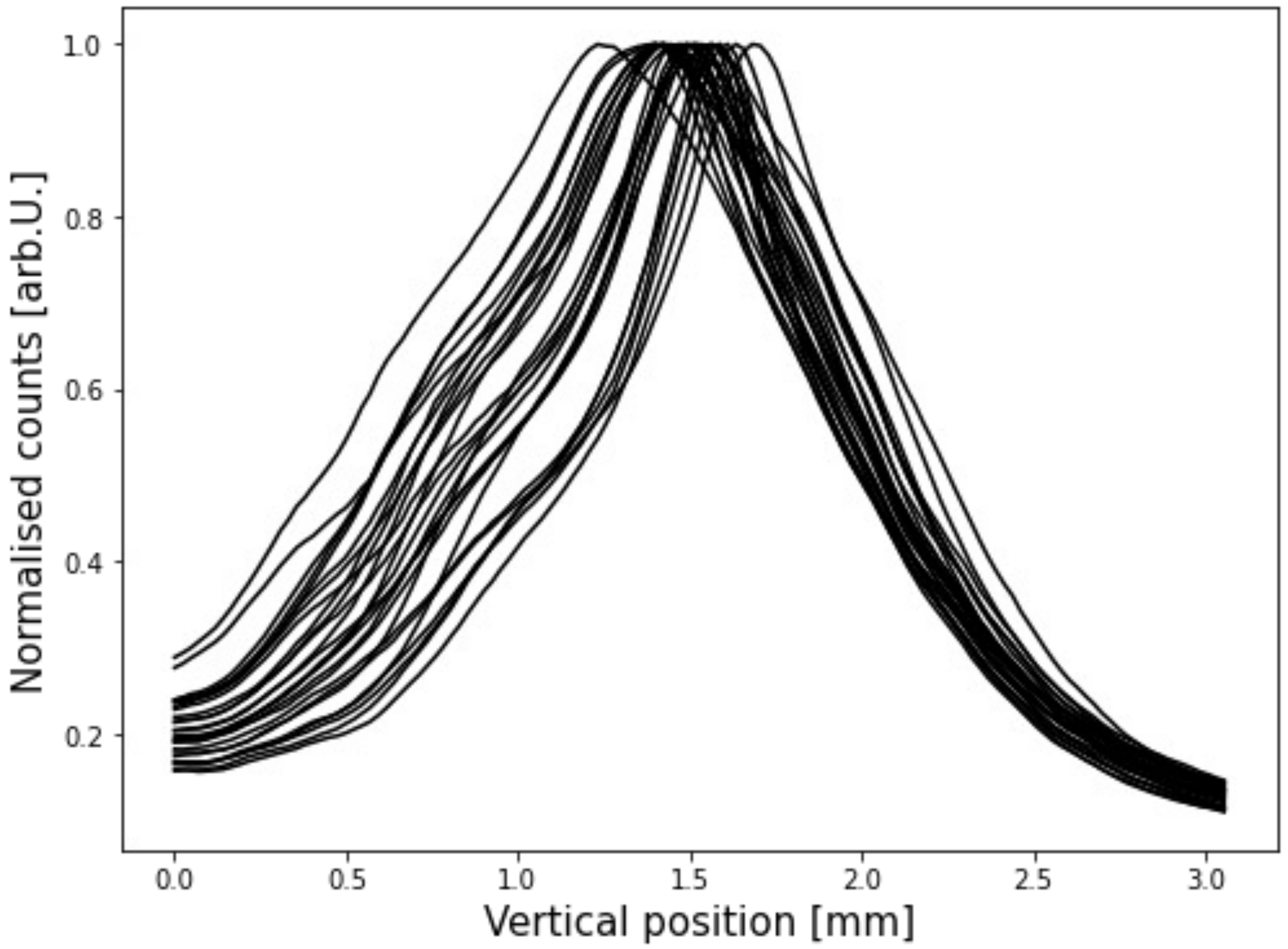


After

Typical beam centroid jitters ~100 microns



Summary and Conclusions

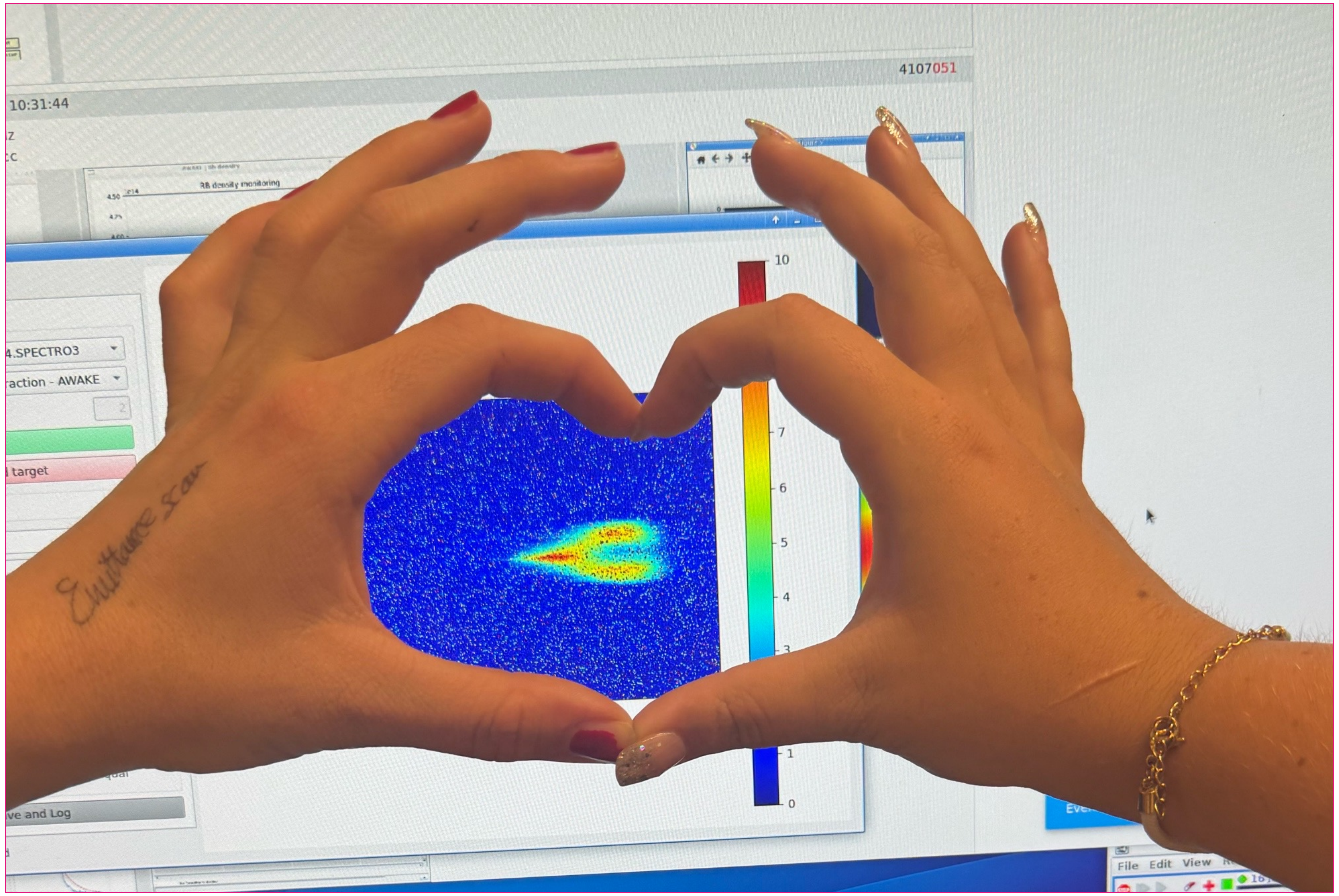
Different experiments require large flexibility of the e-beam setup in terms of:

•Beam waist position (different locations along the vapour source)
•Alignment (on axis: SM and hosing; off-axis: probing wakefield amplitudes)

The addition of YAG screens inside the vapour source allows for the verification of :

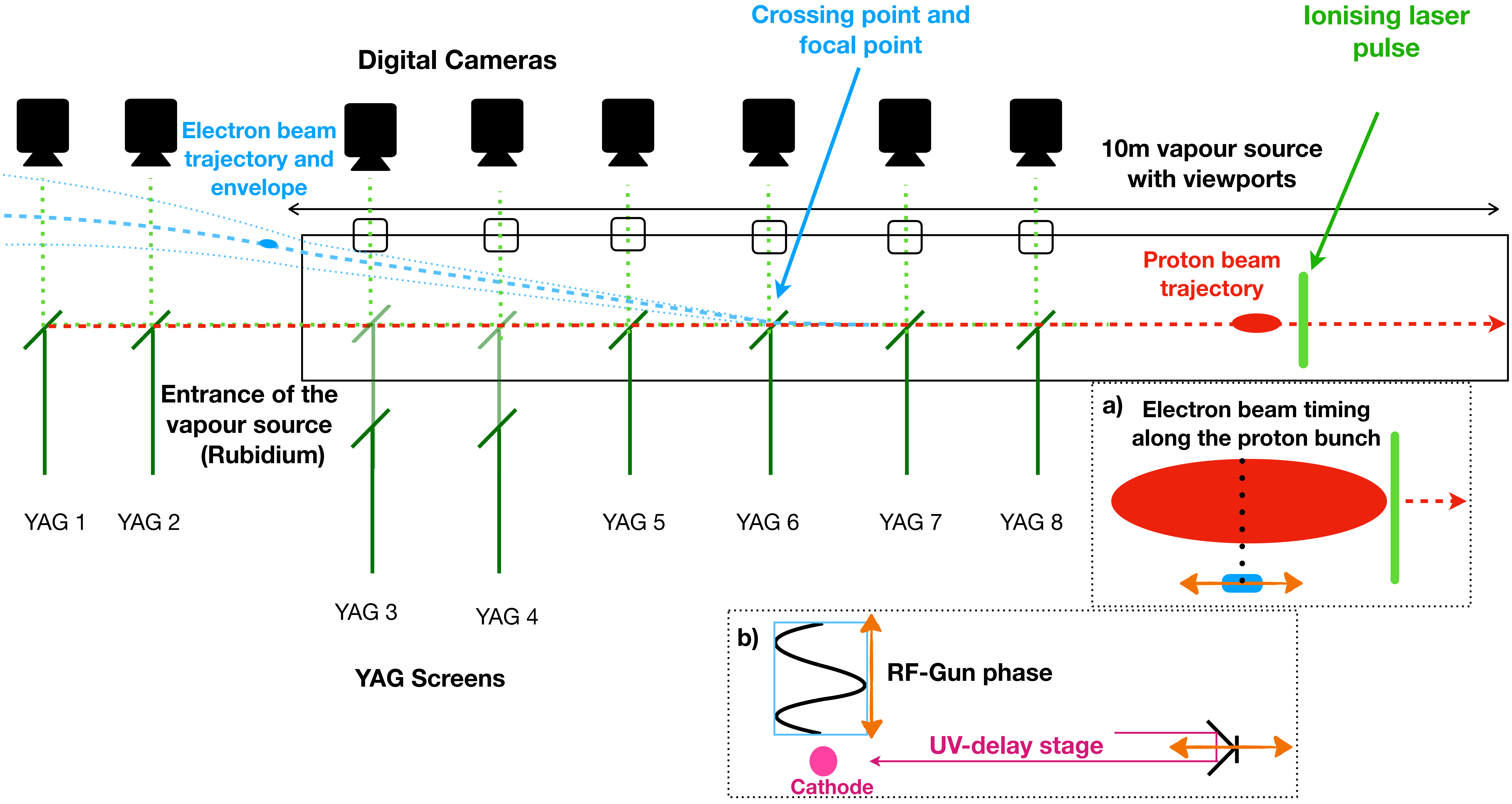
- **electron** and **proton** beam alignment for seeding of SM and hosing as well as external injection of witness particles to probe wakefields
- electron beam optics up to and around focus
- and **determination**, and **mitigation** of any external factors and their effect on the electron bunch (position and shape) => which may compromise experiments => solvable through clear and concise procedures

The End



Thank you for listening!

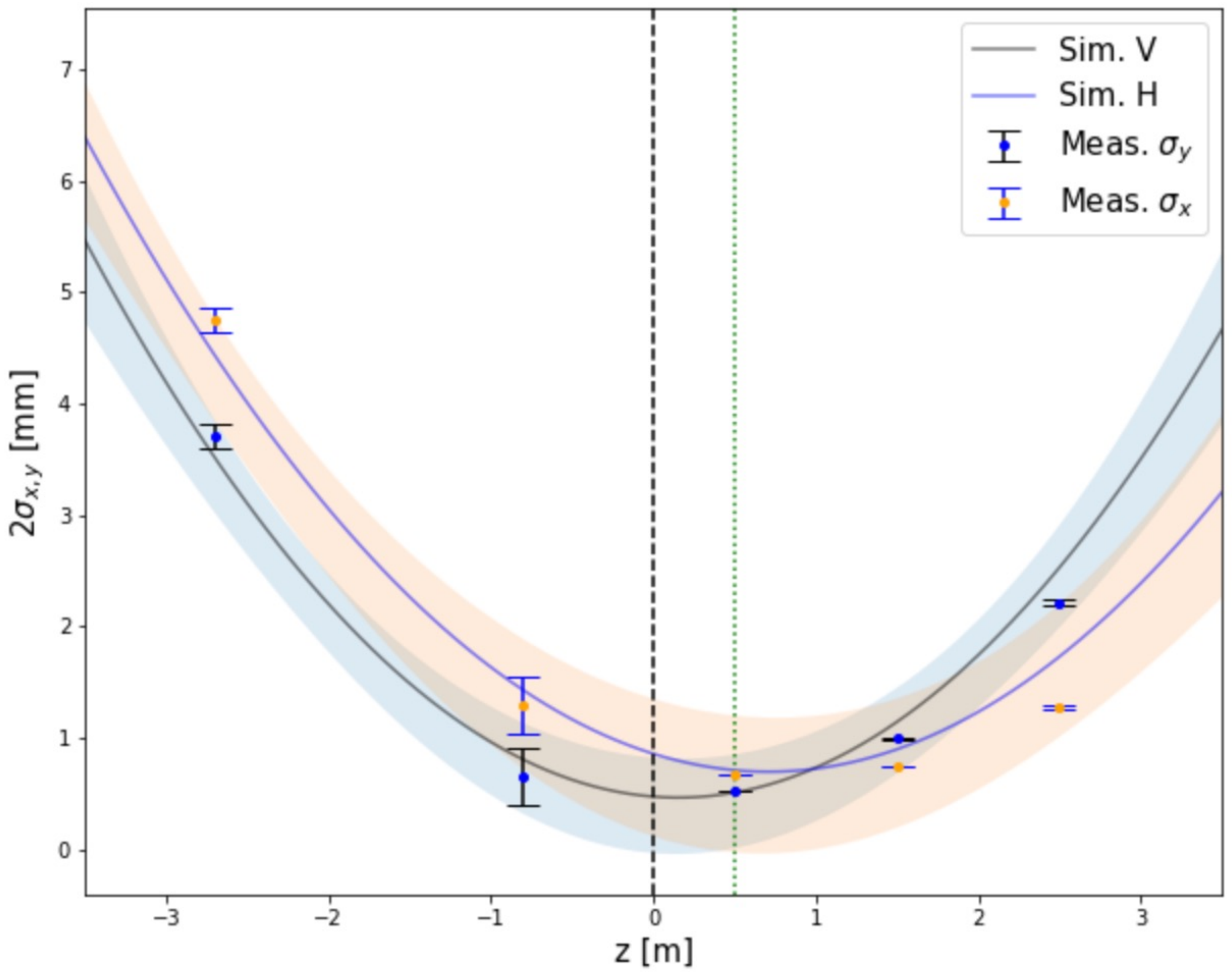
Backup slides



Crossing point and focal point
Ionising laser pulse
Digital Cameras
Electron beam trajectory and envelope
10m vapour source with viewports
Proton beam trajectory
Entrance of the vapour source (Rubidium)
a) Electron beam timing along the proton bunch
YAG 1
YAG 2
YAG 5
YAG 6
YAG 7
YAG 8
YAG 3
YAG 4
YAG Screens
b)
RF-Gun phase
UV-delay stage
Cathode

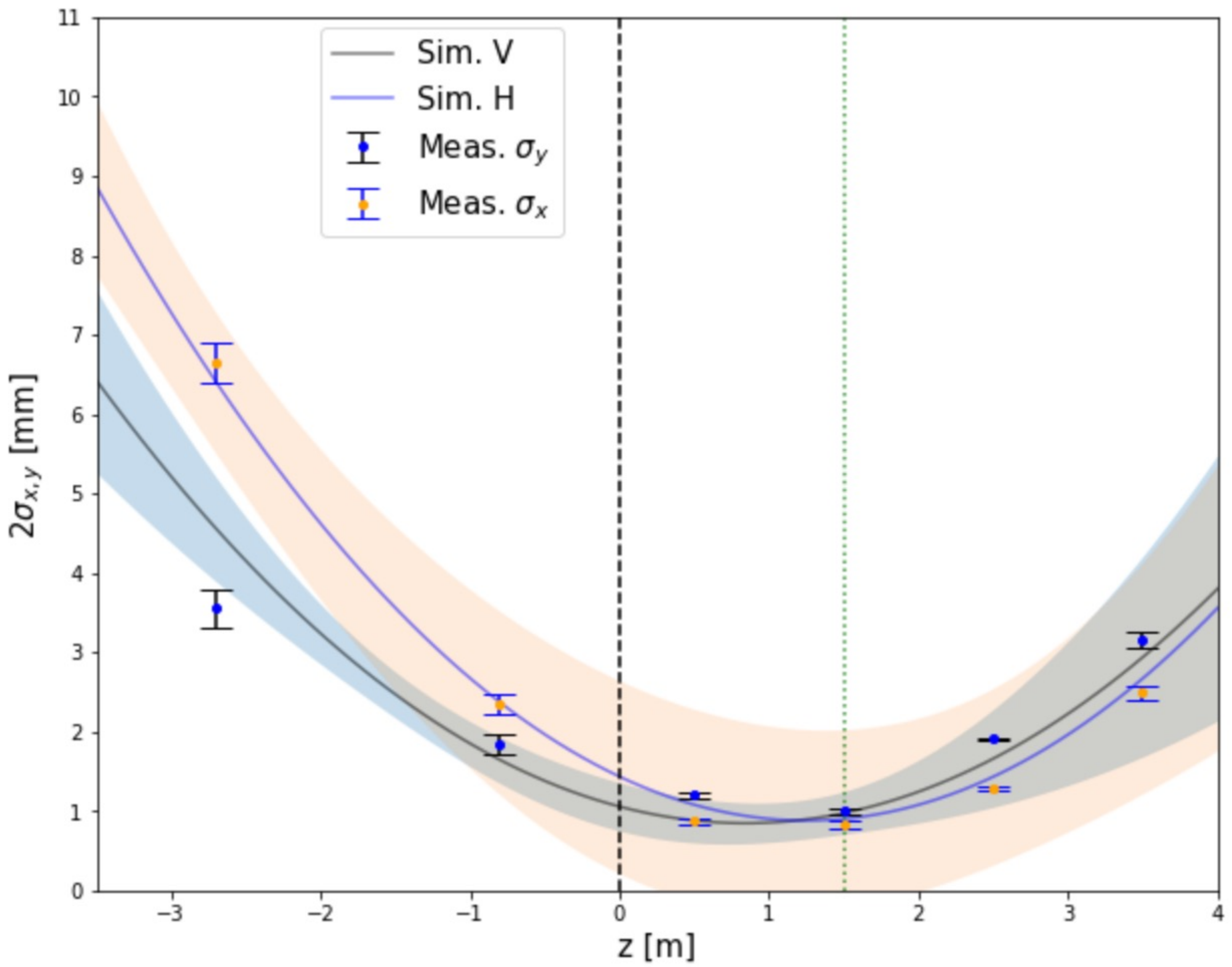
Errorbars are variations in beam size and error on the fit. Centroid jitters over 100 1Hz events.

0.5m optics



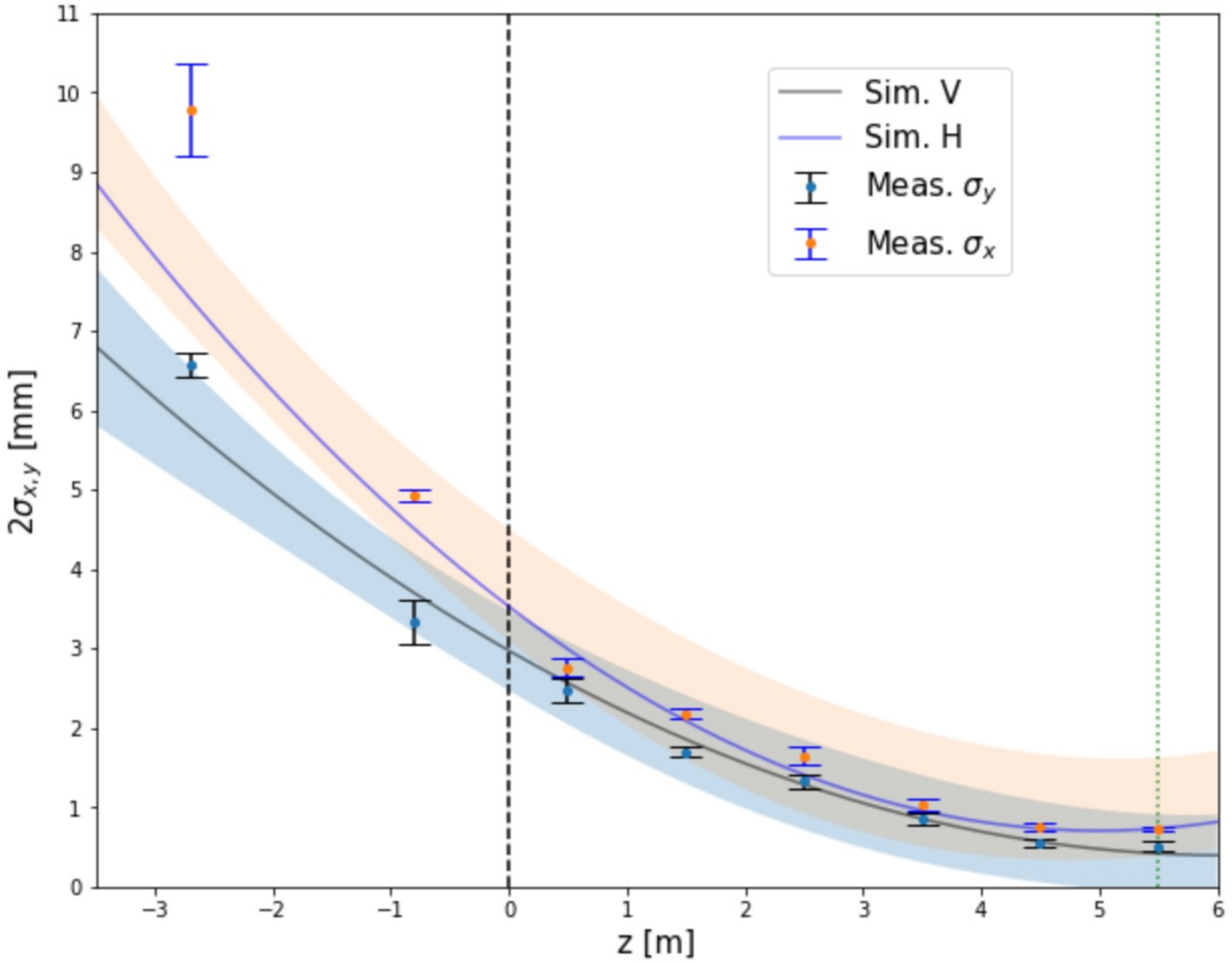
Focus	Charge	Sig_x	Sig_y	Centroid jitter
0.5m	200pC	0.386± 0.019mm	0.295± 0.024mm	(0.030, 0.032)mm
0.5m	400pC	0.668± 0.055mm	0.519± 0.020	(0.047, 0.036)mm

1.5m optics



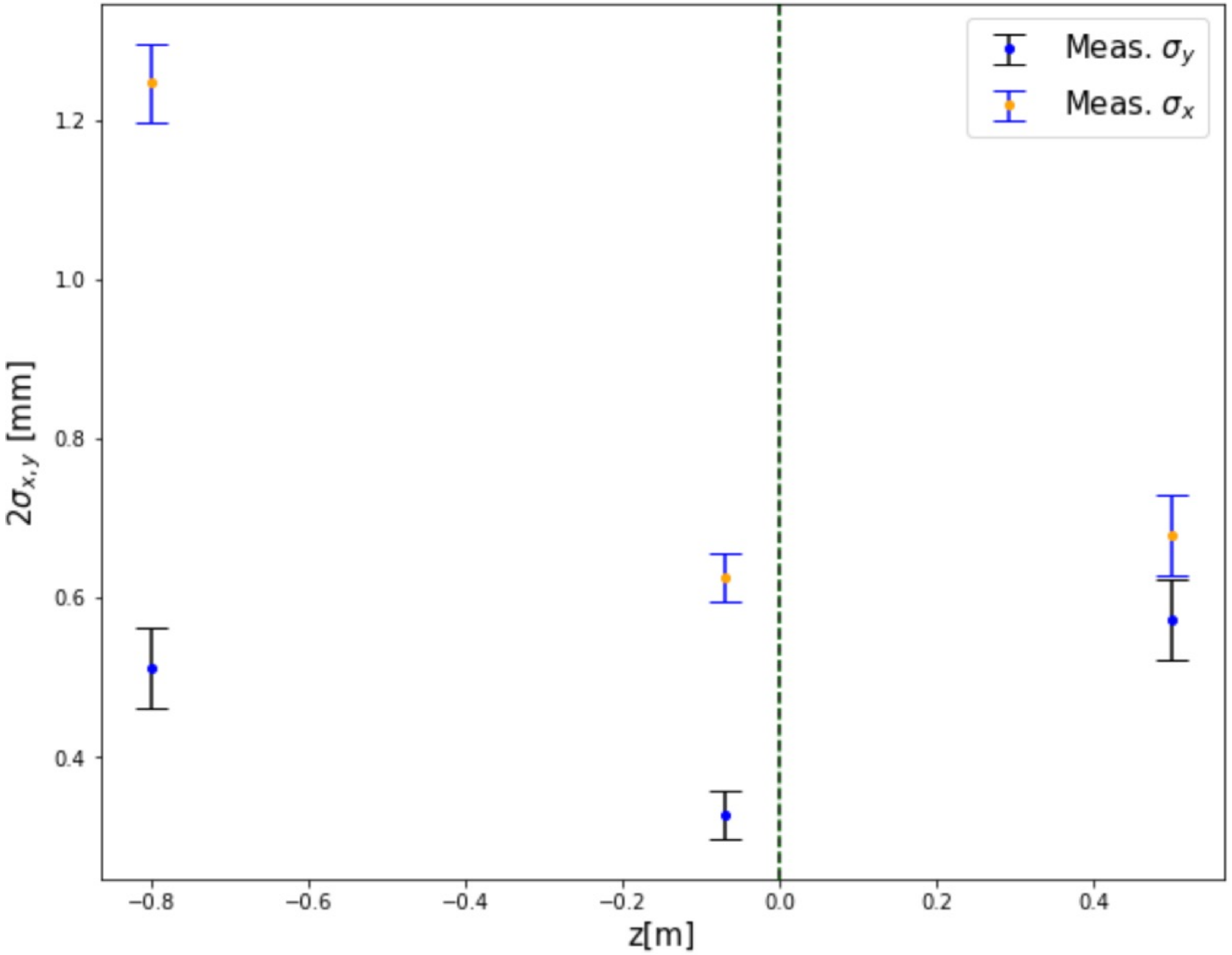
Focus	Charge	Sig_x	Sig_y	Centroid jitter
1.5m	200pC	0.441± 0.023mm	0.349± 0.017mm	(0.051, 0.042)mm
1.5m	400pC	0.498± 0.022mm	0.418± 0.047mm	(0.090, 0.075)mm
1.5m	800pC	0.687± 0.045mm	0.768± 0.058mm	(0.102, 0.097)mm

5.5m optics



Focus	Charge	Sig_x	Sig_y	Centroid jitter
5.5m	200pC	0.411± 0.022mm	0.513± 0.043mm	(0.043, 0.040)mm
5.5m	400pC	0.650± 0.080mm	0.582± 0.050mm	(0.081, 0.056)mm
5.5m	800pC	0.764± 0.098mm	0.693± 0.059mm	(0.101, 0.079)mm

Focus at iris beamsizes measured on BTV54, BTVEXPVOL and CAM1

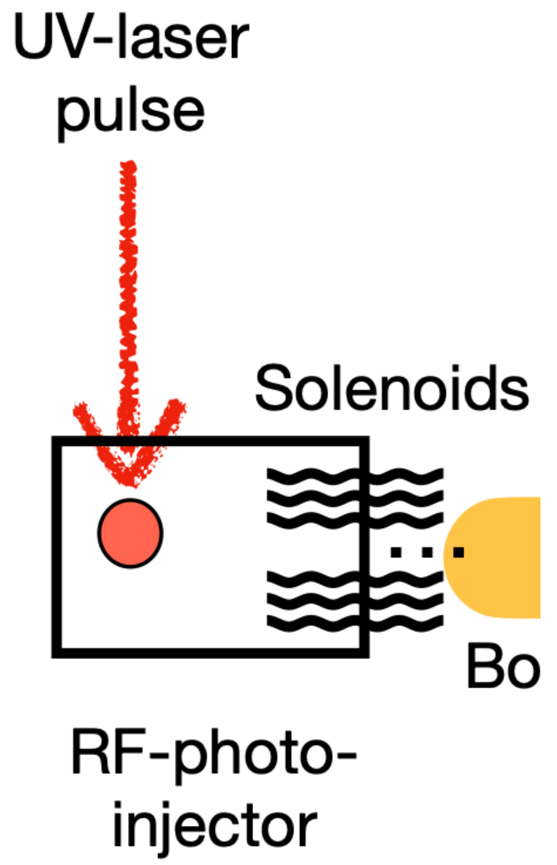


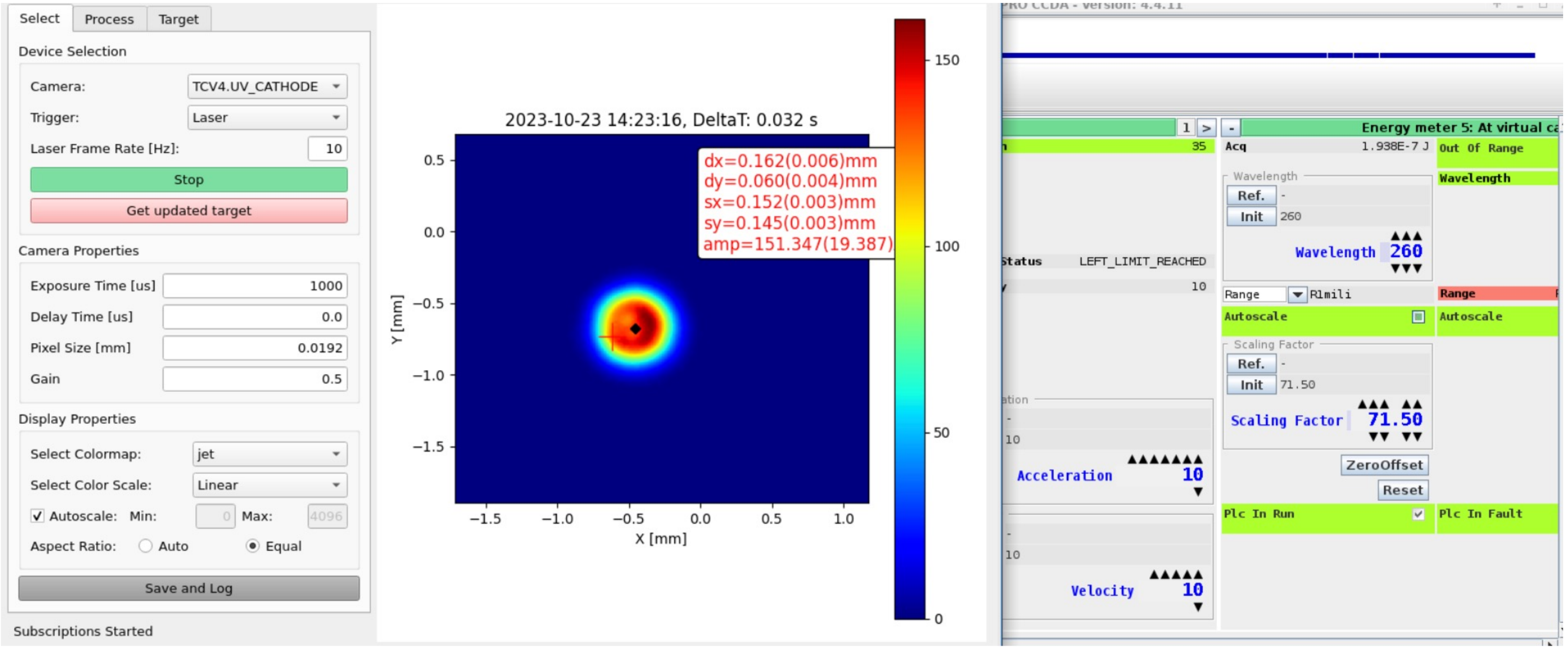
Focus	Charge	Sig_x	Sig_y	Centroid jitter
0.5m	200pC	0.386± 0.019mm	0.295± 0.024mm	(0.030, 0.032)mm
0.5m	400pC	0.668± 0.055mm	0.519± 0.020	(0.047, 0.036)mm

Errorbars plotted are variations in beam size and error on the fit.

Electron beam setup:

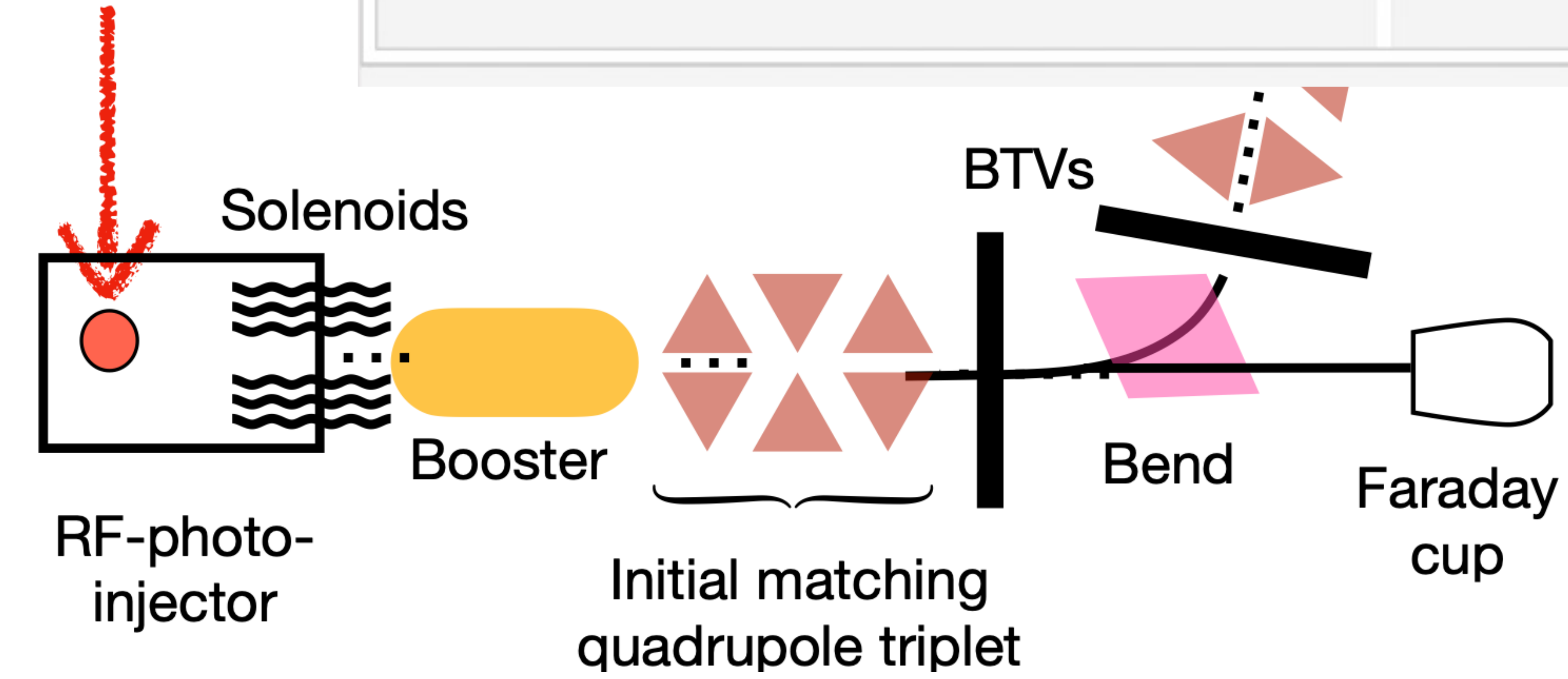
- Electron creation: illuminating a Cs_2Te cathode with a UV laser pulse (typical spot size: ~1mm, average energy: ~200nJ, top hat intensity profile).





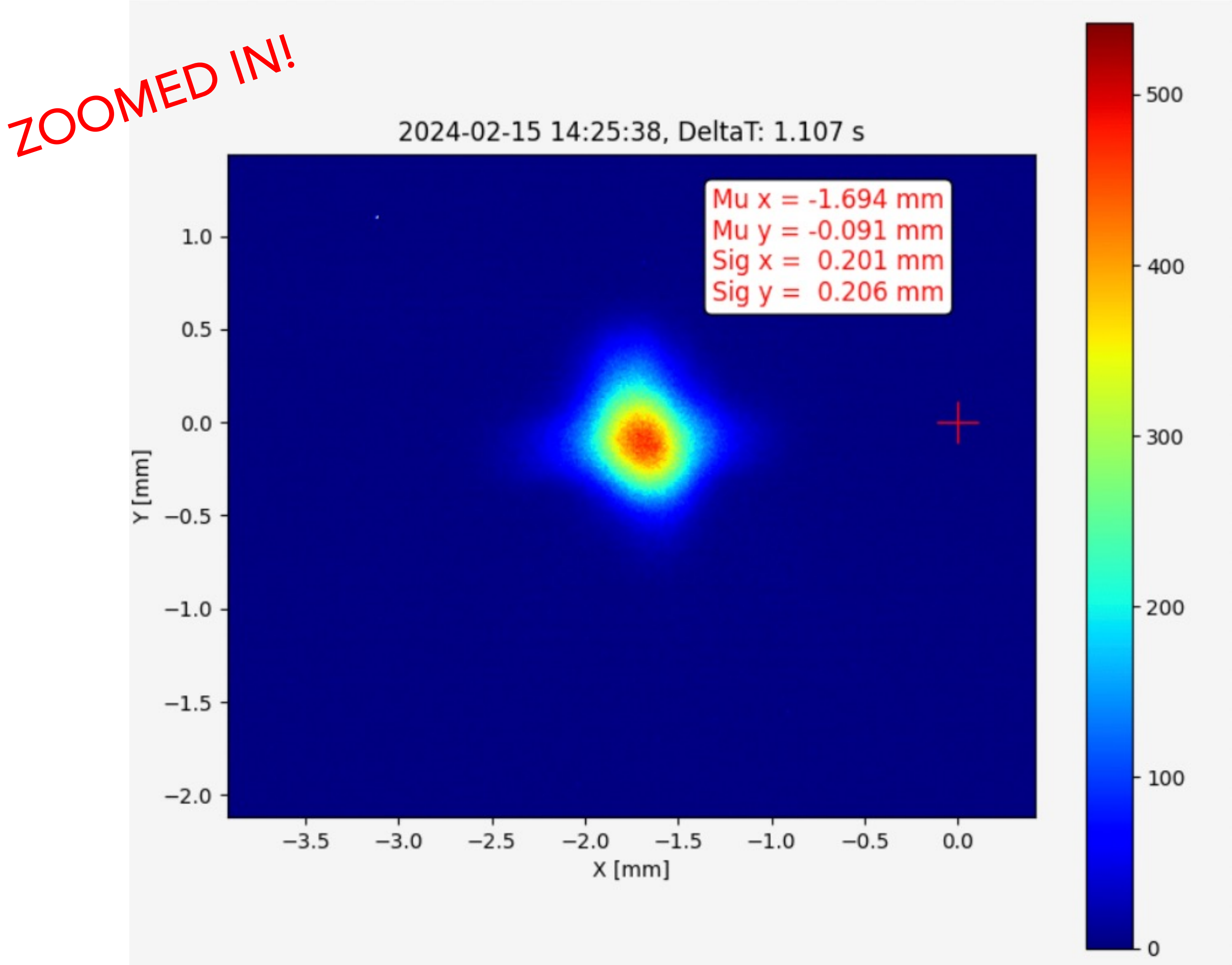
Electron beam setup:

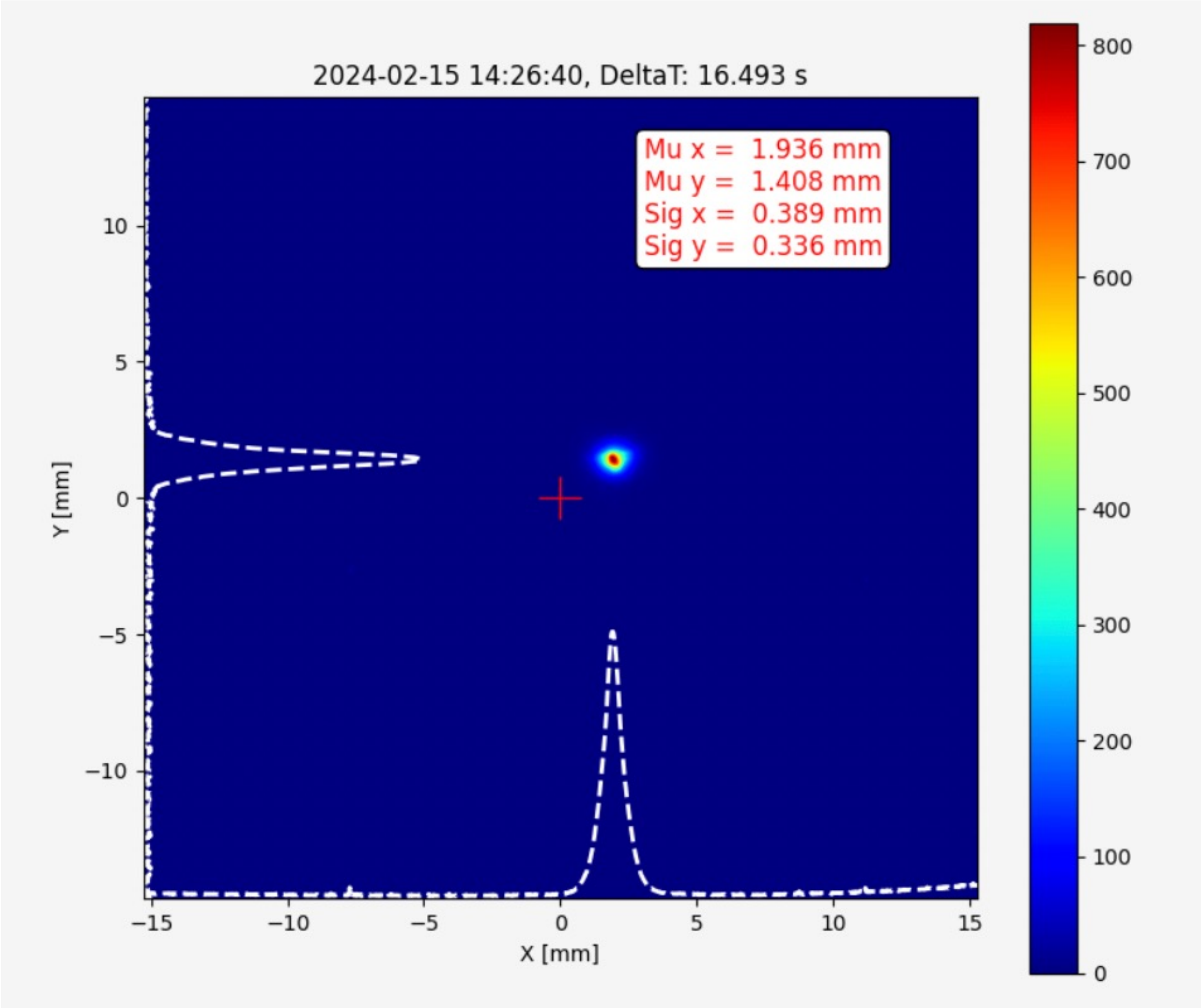
- Electron creation: illuminating a Cs_2Te cathode with a UV laser pulse (typical spot size: ~1mm, average energy: ~200nJ, top hat intensity profile).
- These bunched electrons are then accelerated to an energy of ~5MeV in an S-band RF-photo-injector.
- Two low-energy solenoids located after the photo-injector focus the electrons inside the 1m-long travelling wave booster structure, where they are further accelerated to ~19MeV, and hand them over to the transfer line.
- Charge can be varied between 100-800 pC (measured at a Faraday cup)

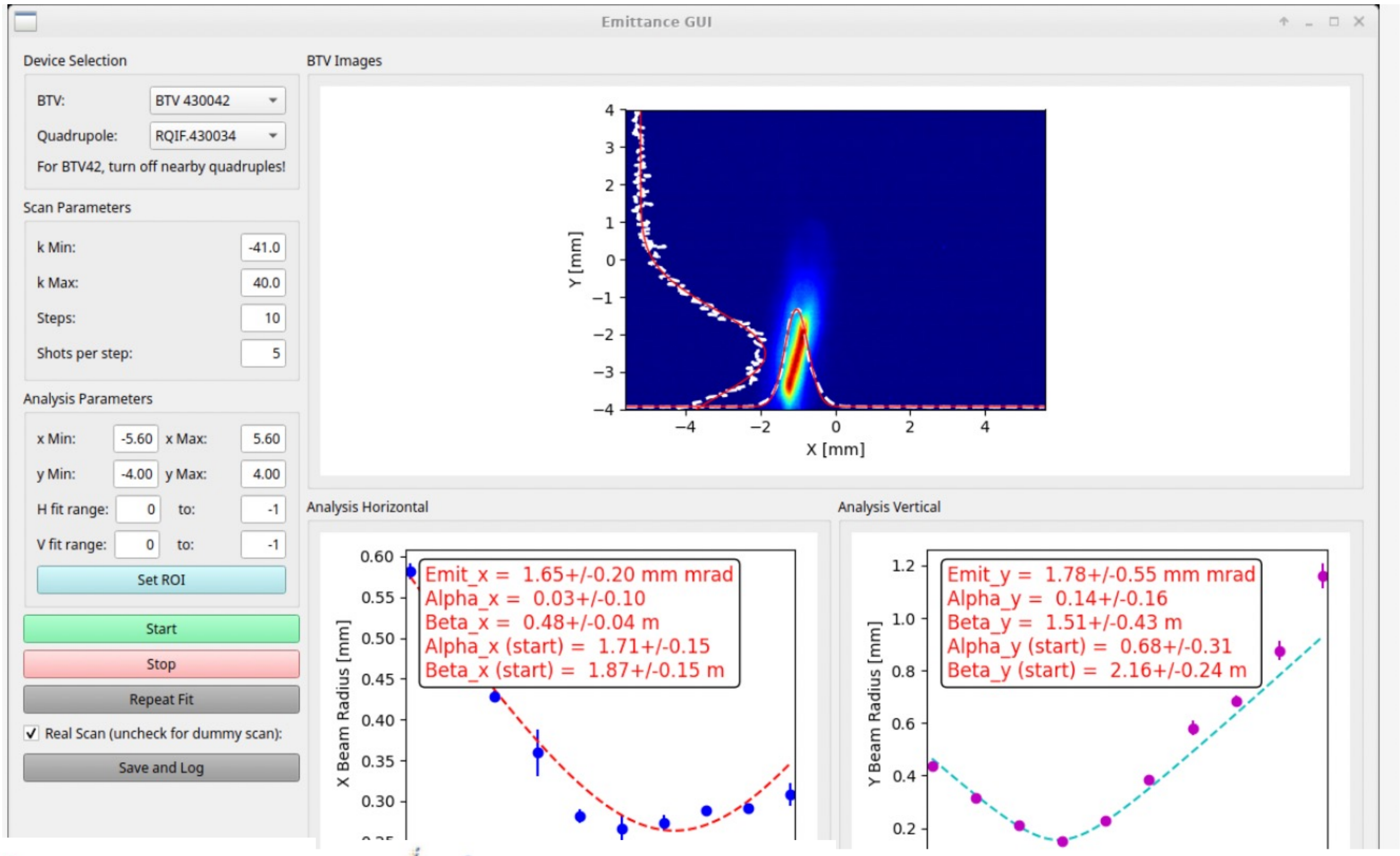


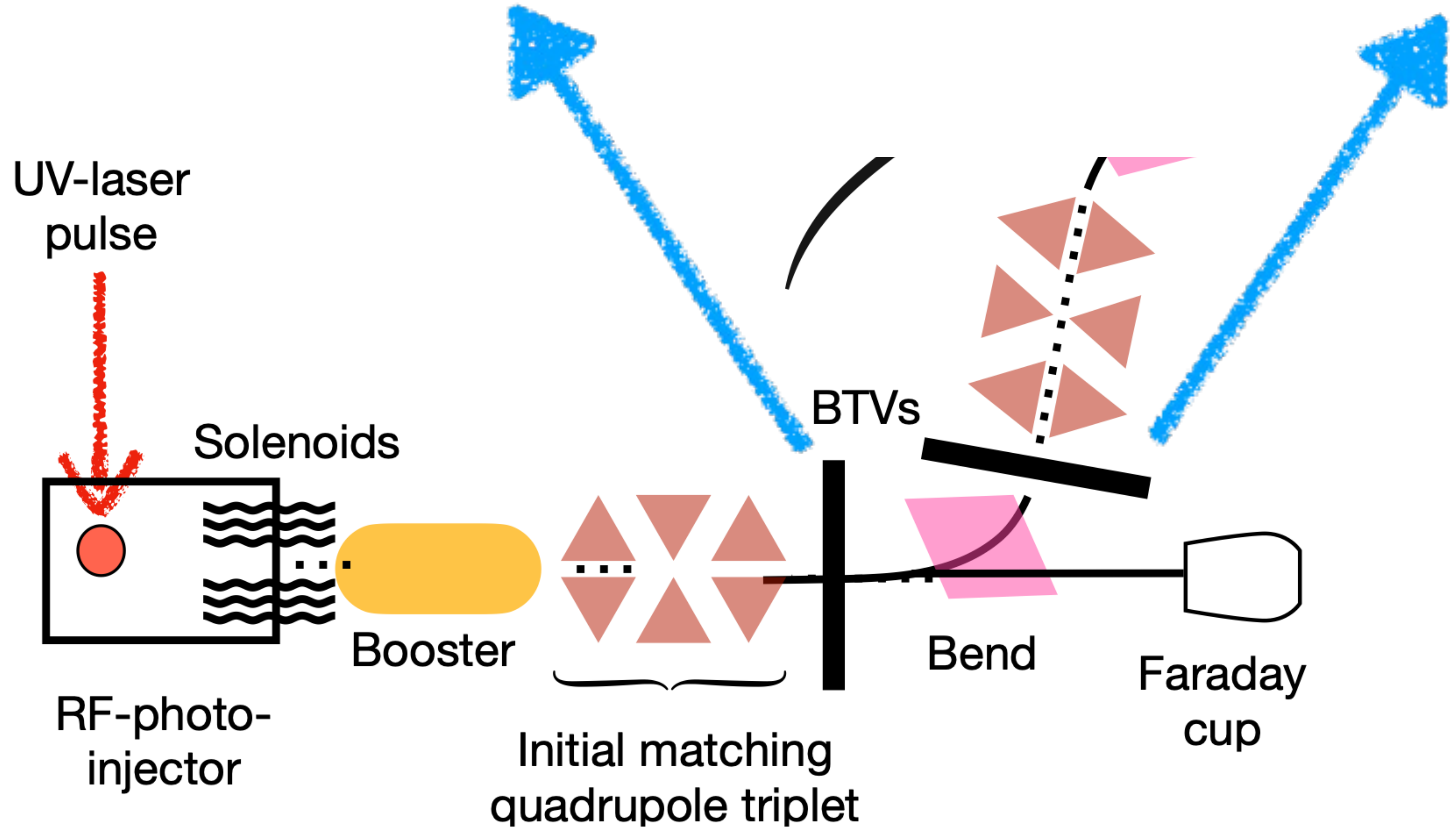
Electron beam setup:

- Emittance scan is performed at the first beam screen (BTV)
- Via tomographic reconstruction the beam out of the gun is matched to the beam line (Vittorio Bencini)
- Optical setup is done via numerical optimisation



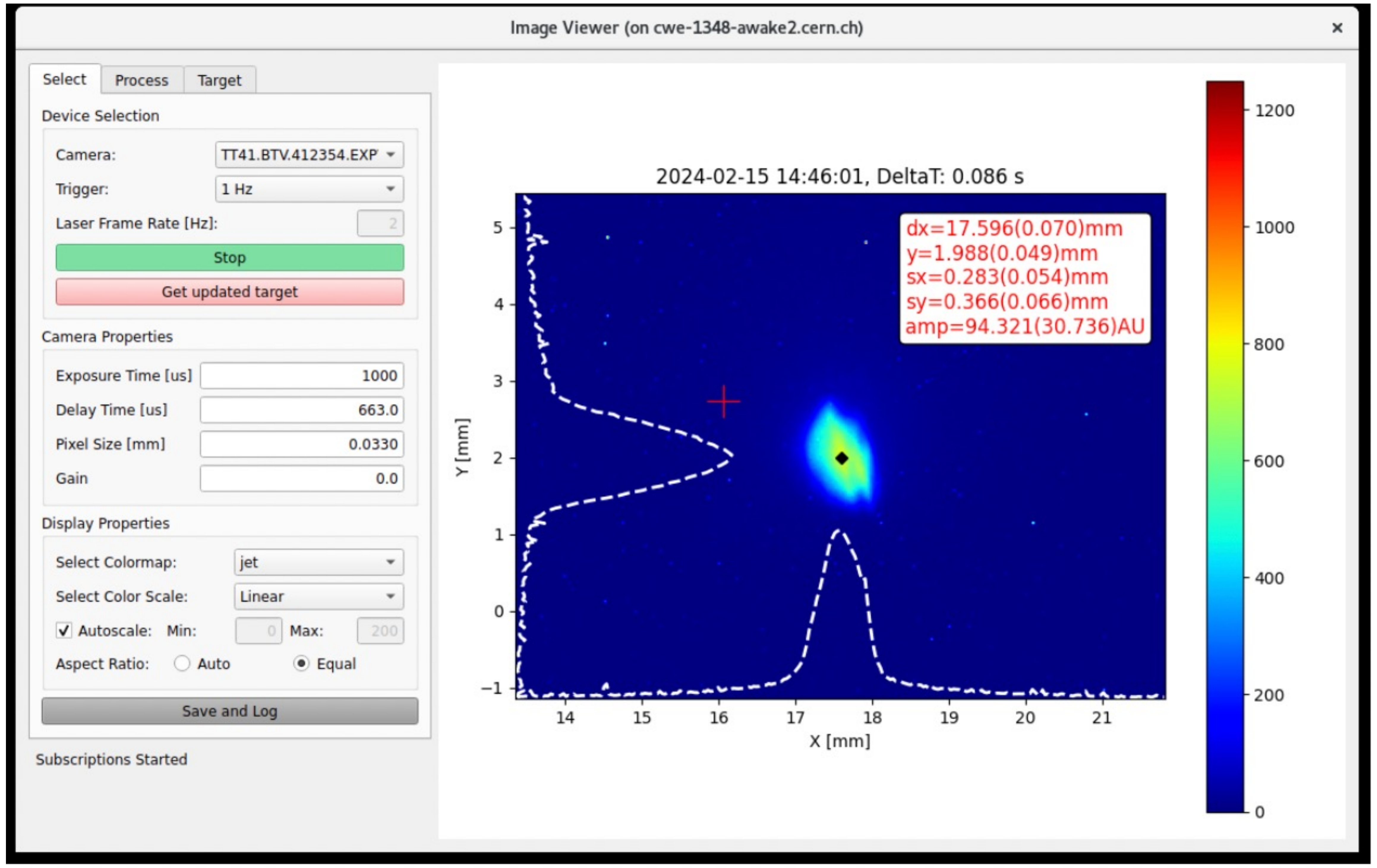


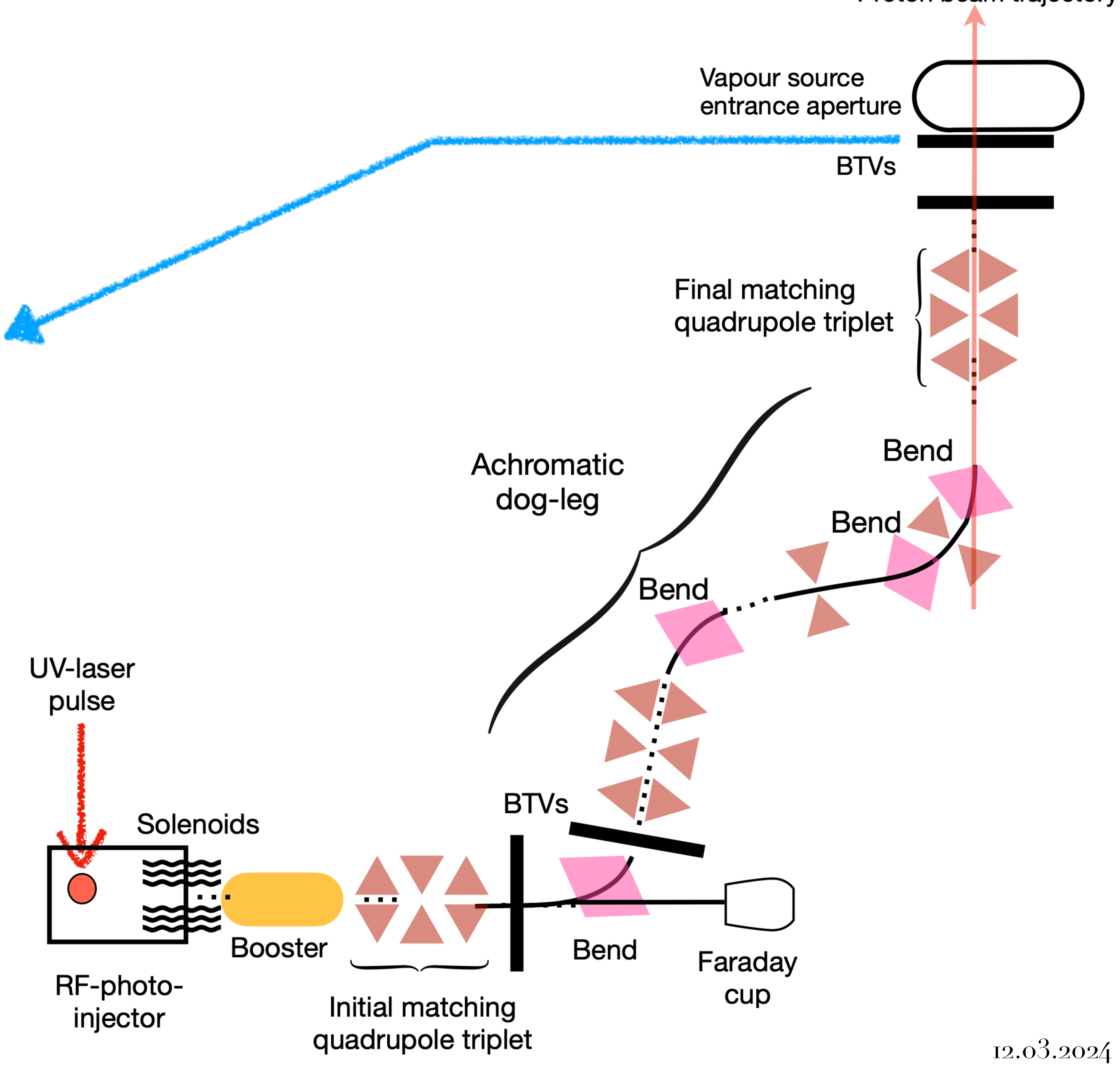




Electron beam setup:

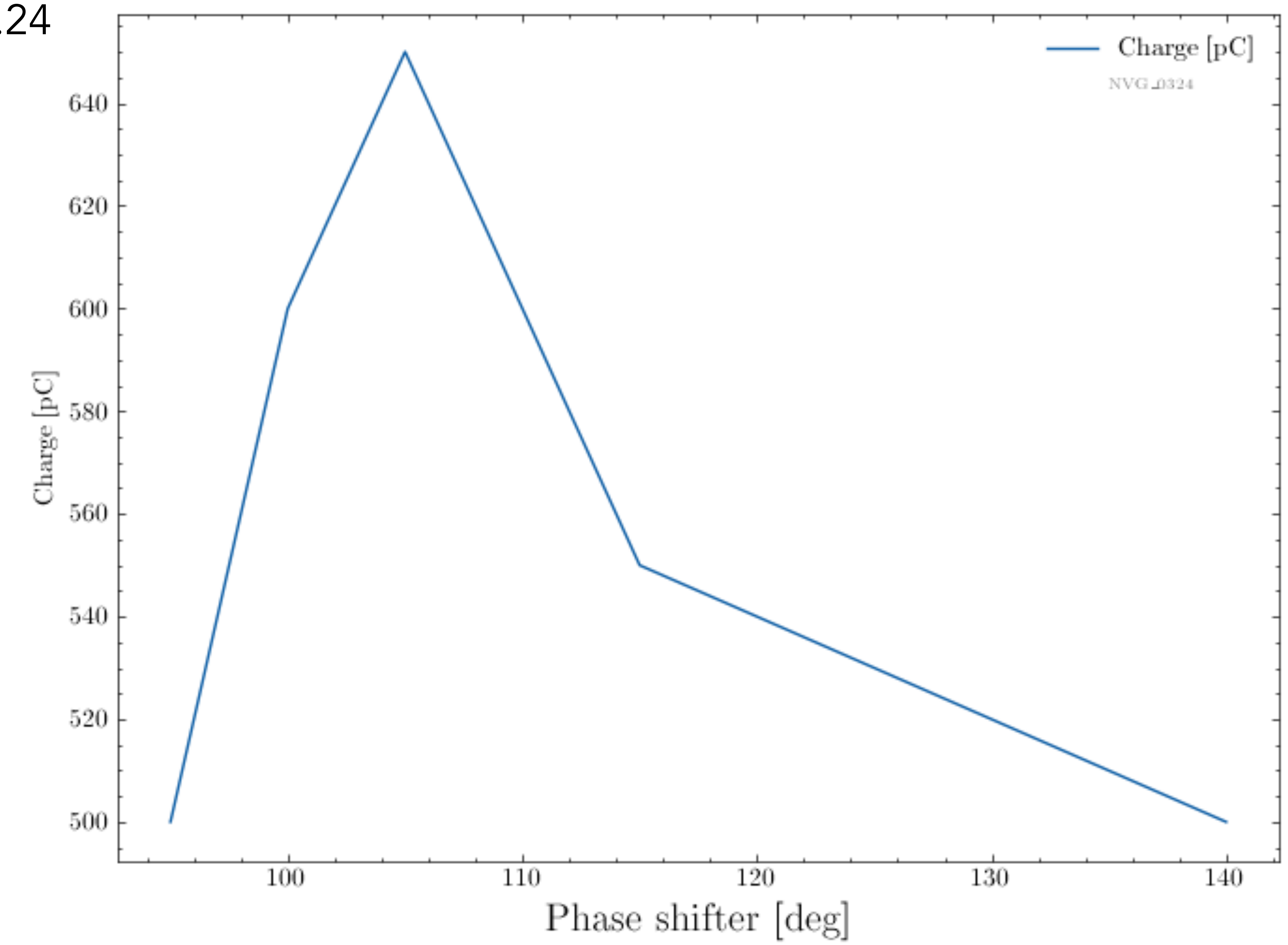
- Using the initial and final quadrupole triplet the beam waist is set at the location of injection
- Measurements compared to simulated (MADX tracking) beam sizes

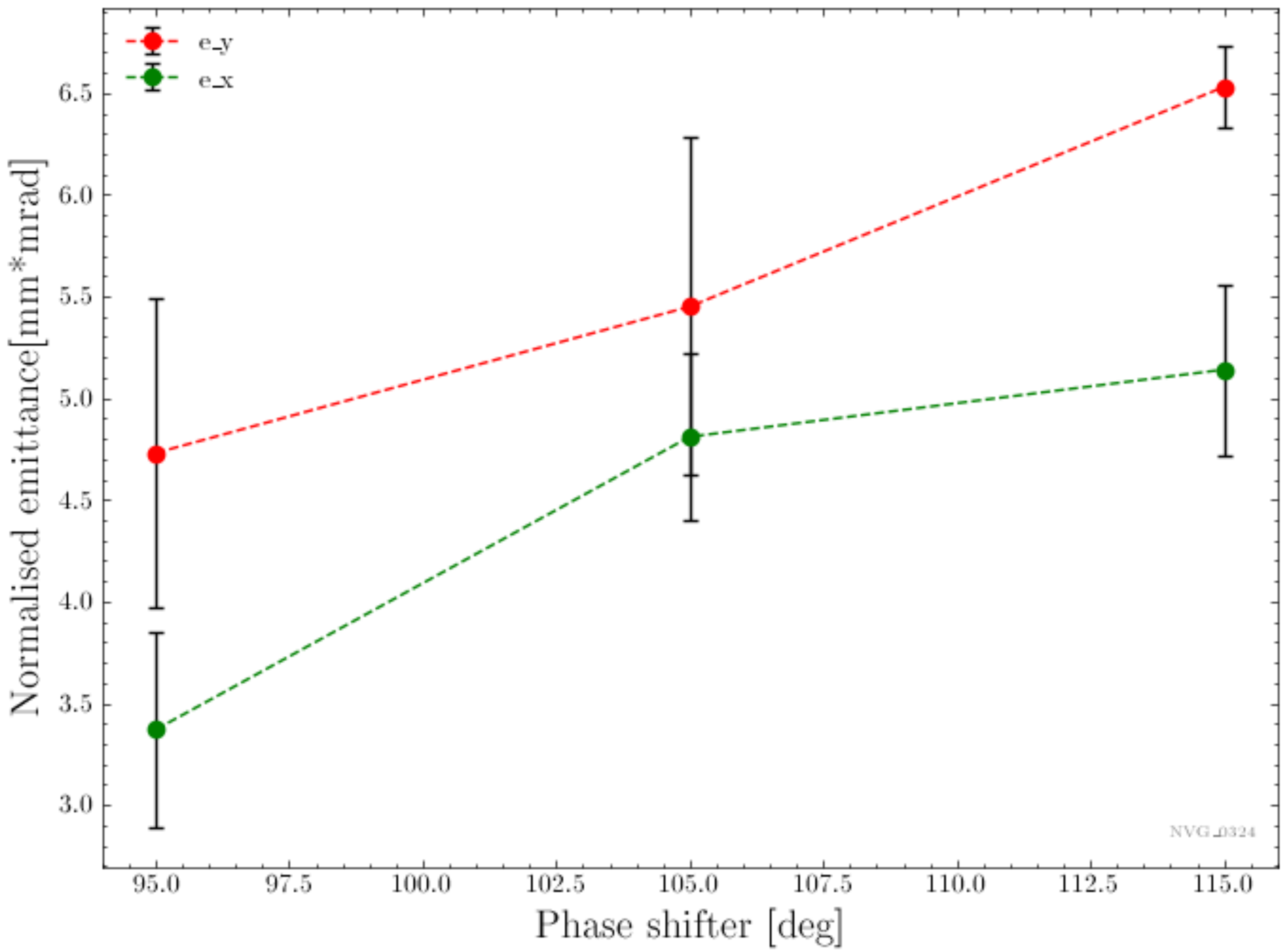


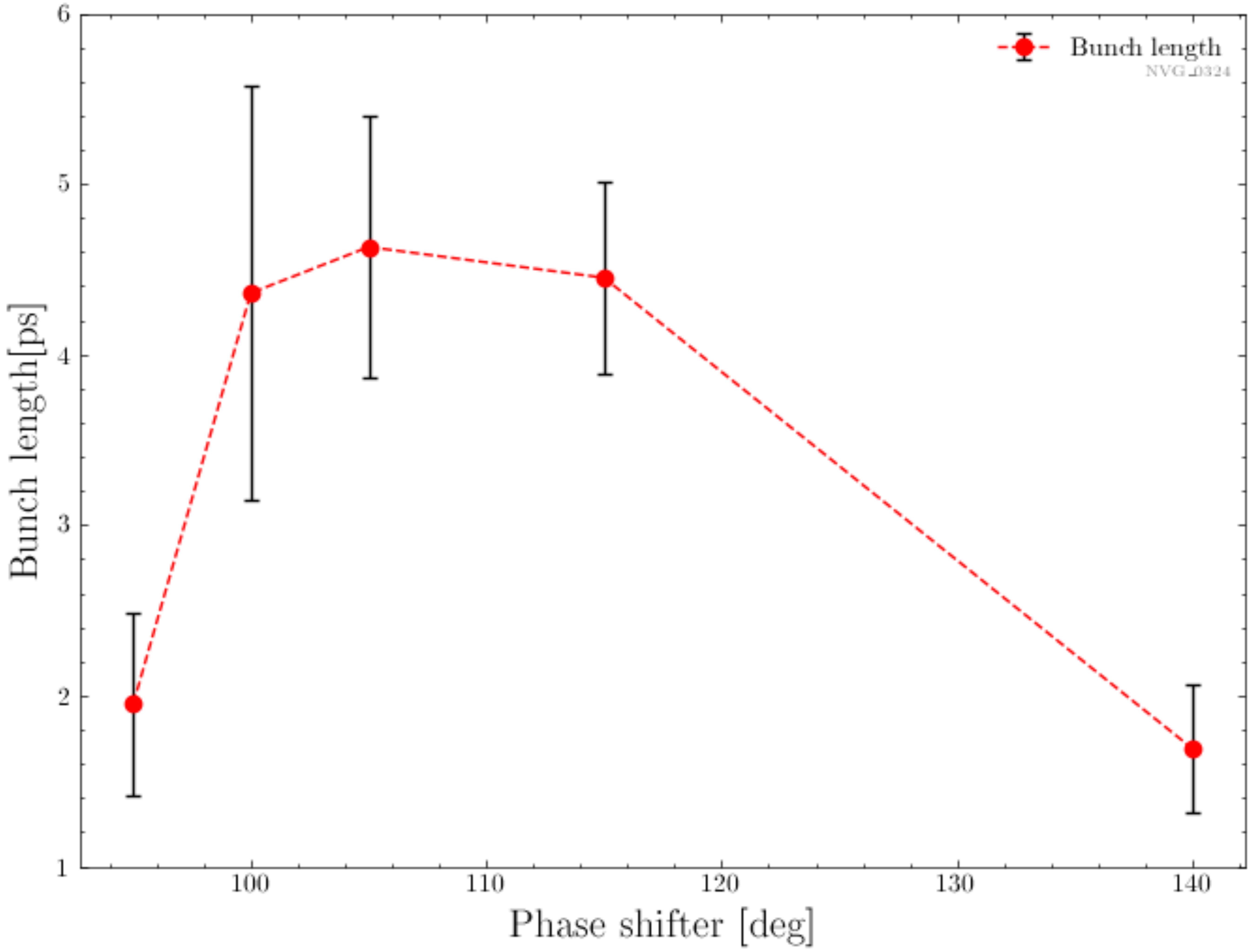


1.24

Bunch length, normalised emittance and charge as a function of RF gun phase



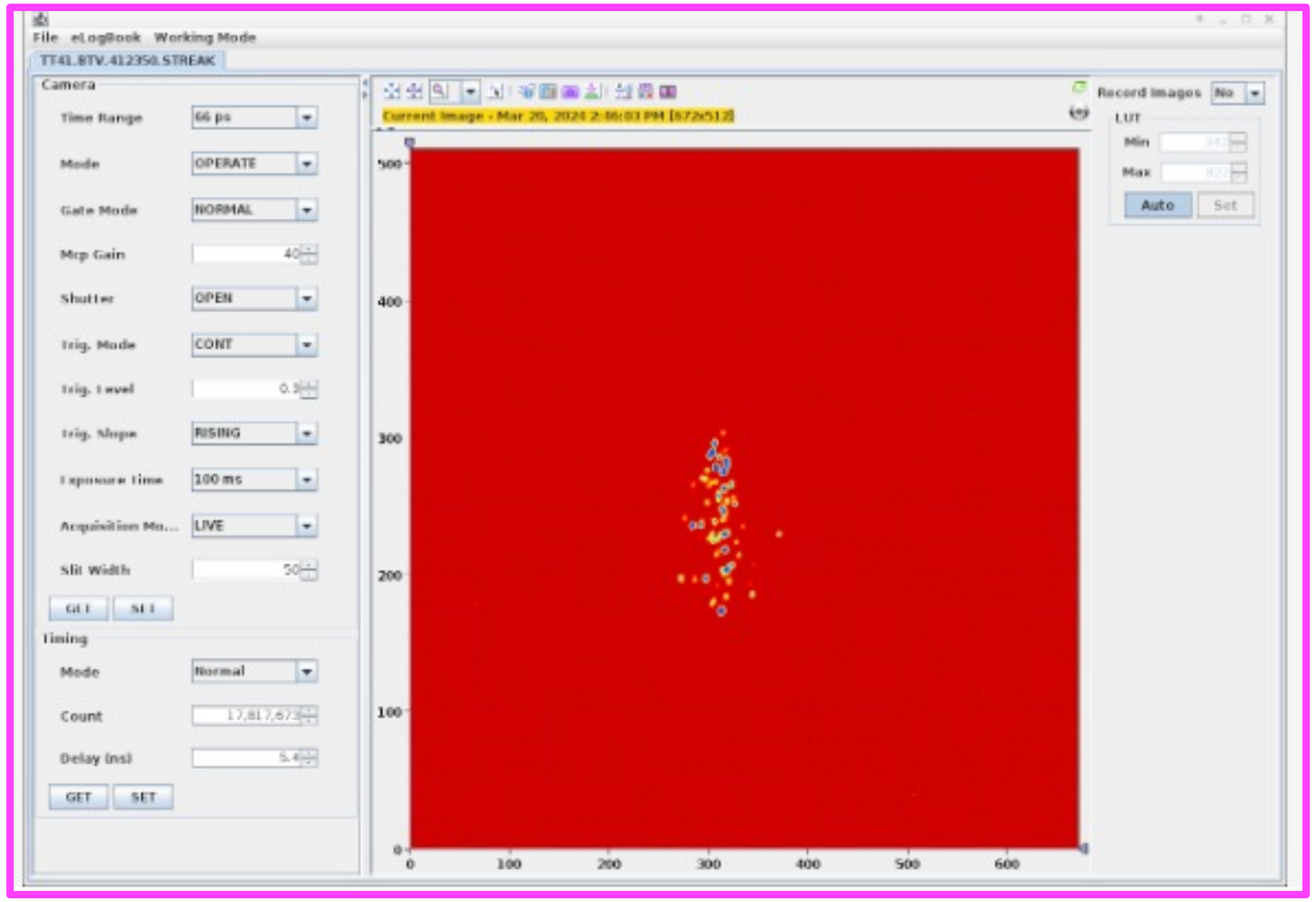




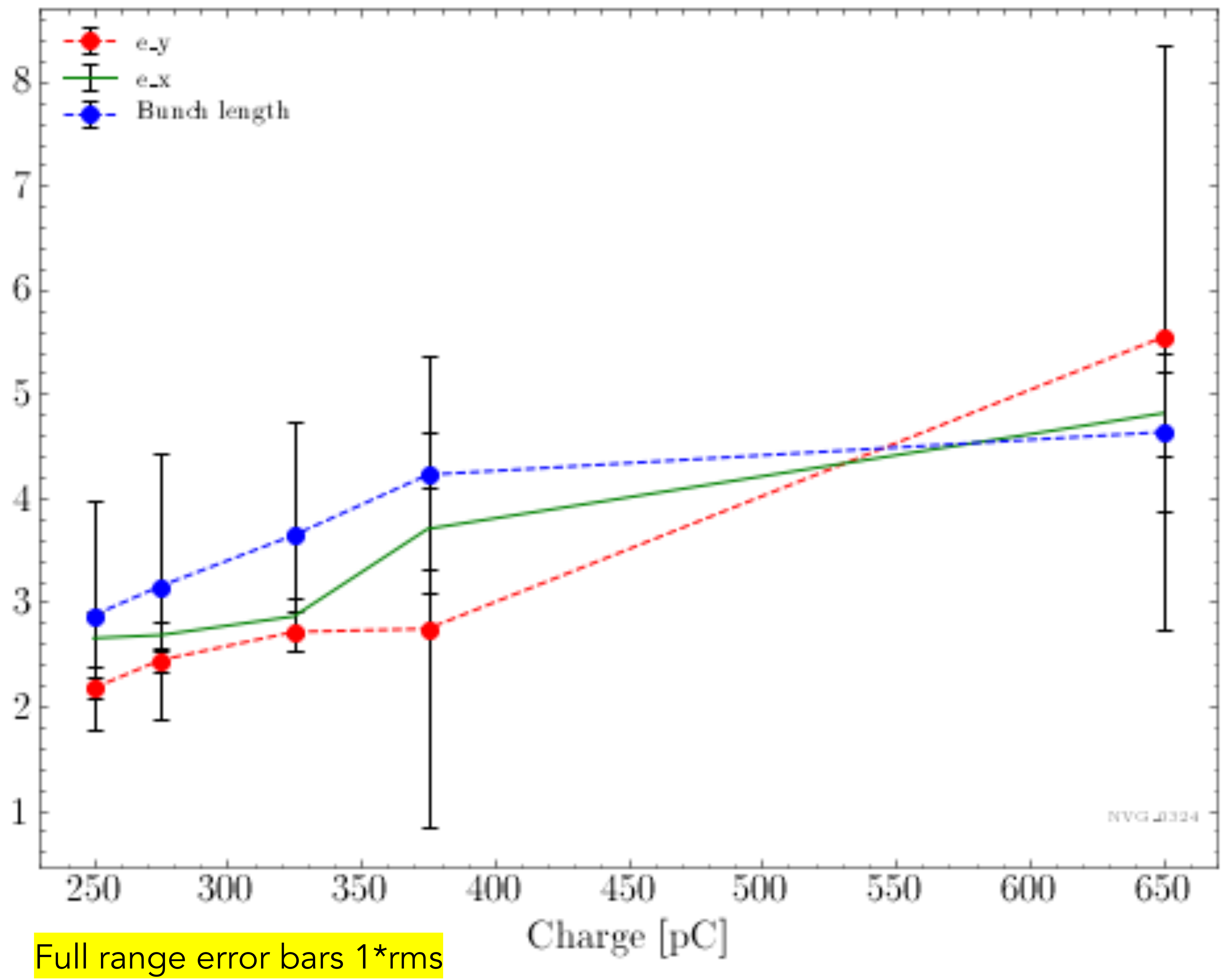
1.24

Phase shifter 1105, WG 342, 0mm

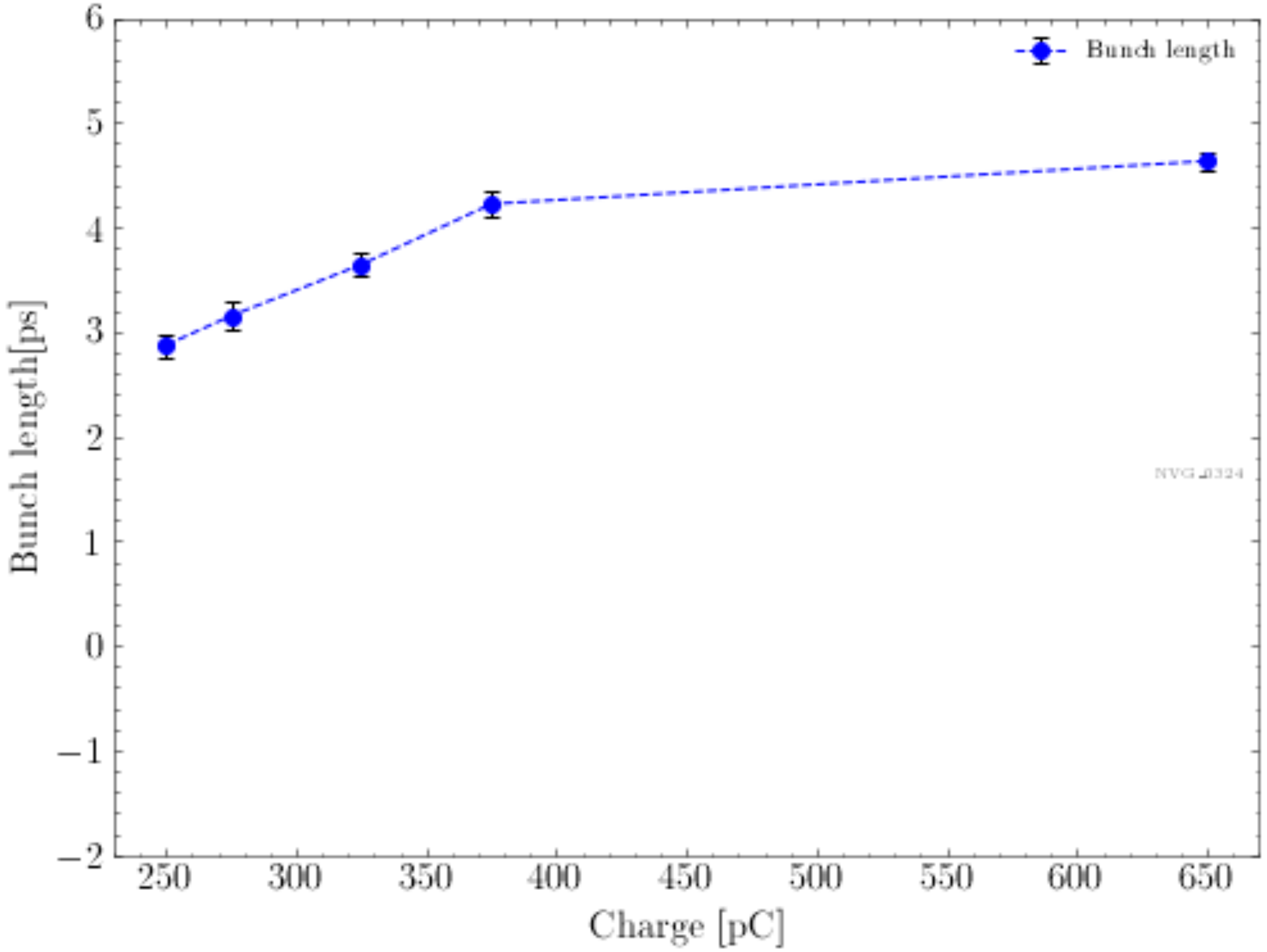
Charge	Emittance mm*mrad	Length ps
Iris 300 375pC	(3.70, 2.74)	4.22± 1.14
Iris 200 325pC	(2.86, 2.71)	3.64±1.1
Iris min 275pC	(2.68, 2.44)	3.15± 1.28
Iris min with OD+0.3: 250pC	(2.65, 2.17)	2.87±1.1
Iris 400: 650pC	(4.81, 5.45)	4.63±0.77



Bunch length and normalised emittance as a function of charge; phase fixed; timing fixed after realignment



Full range error bars 1*rms



Rms/sqrt(N): N=100

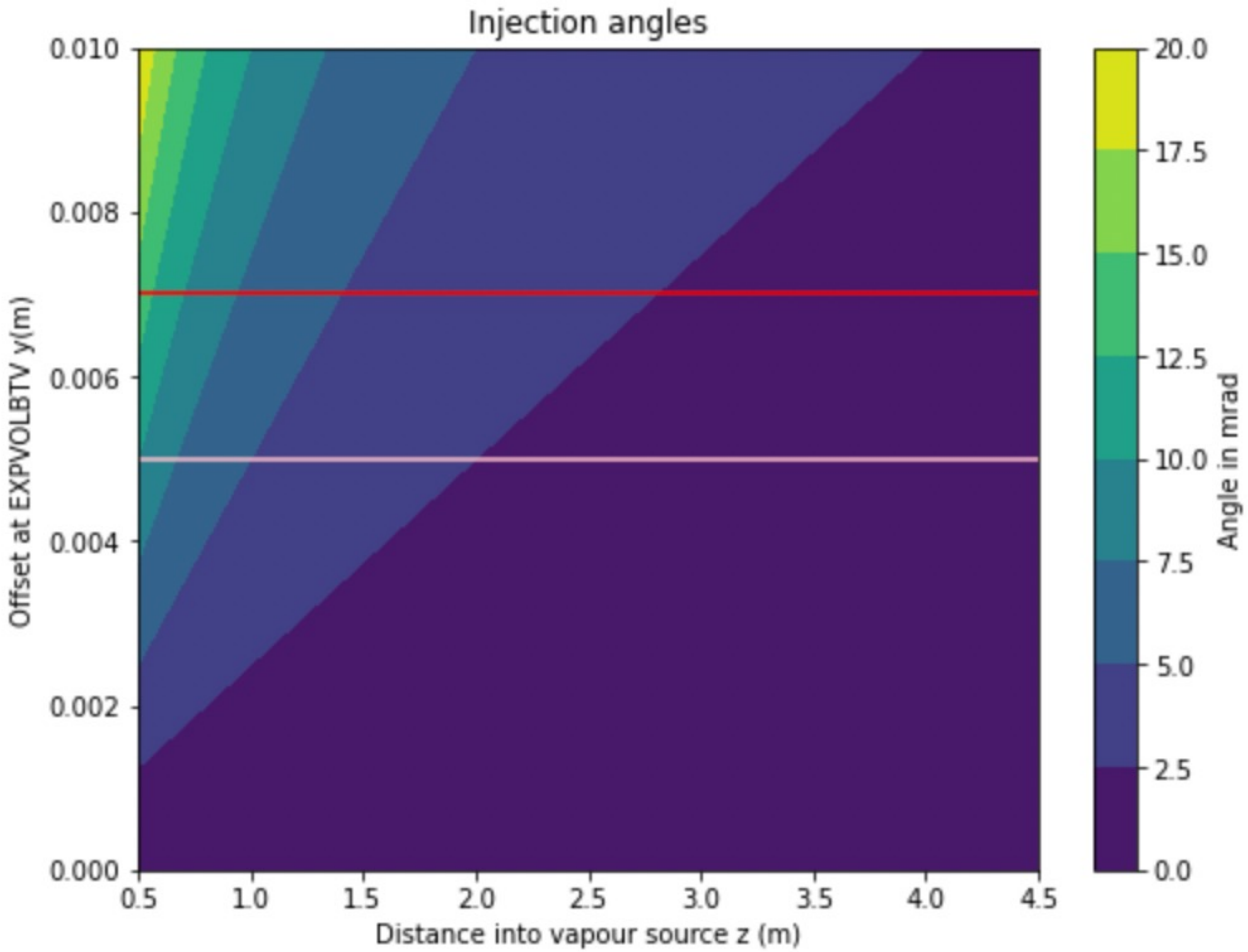
- Performed momentum matching (adjusts beamline magnets to fit new beam with certain momentum).

Estimation of injection angle and limitations for large z_e

e.g. take 2mm (two standard deviations) wide beam. In order to not have cutting at entrance => max offset 7mm (red line), 5mm max offset for beams max 4mm wide (pink line)

Angles assuming straight line trajectories (0.5m-4.5m)

- Wide possibility of injection angles; can cover up to 4.5m with same angle (max up to 5mrad for z=0.5m,1.5m and 2.5m) then below 2.5mrad.



With the help of J.P.T. Salvesen

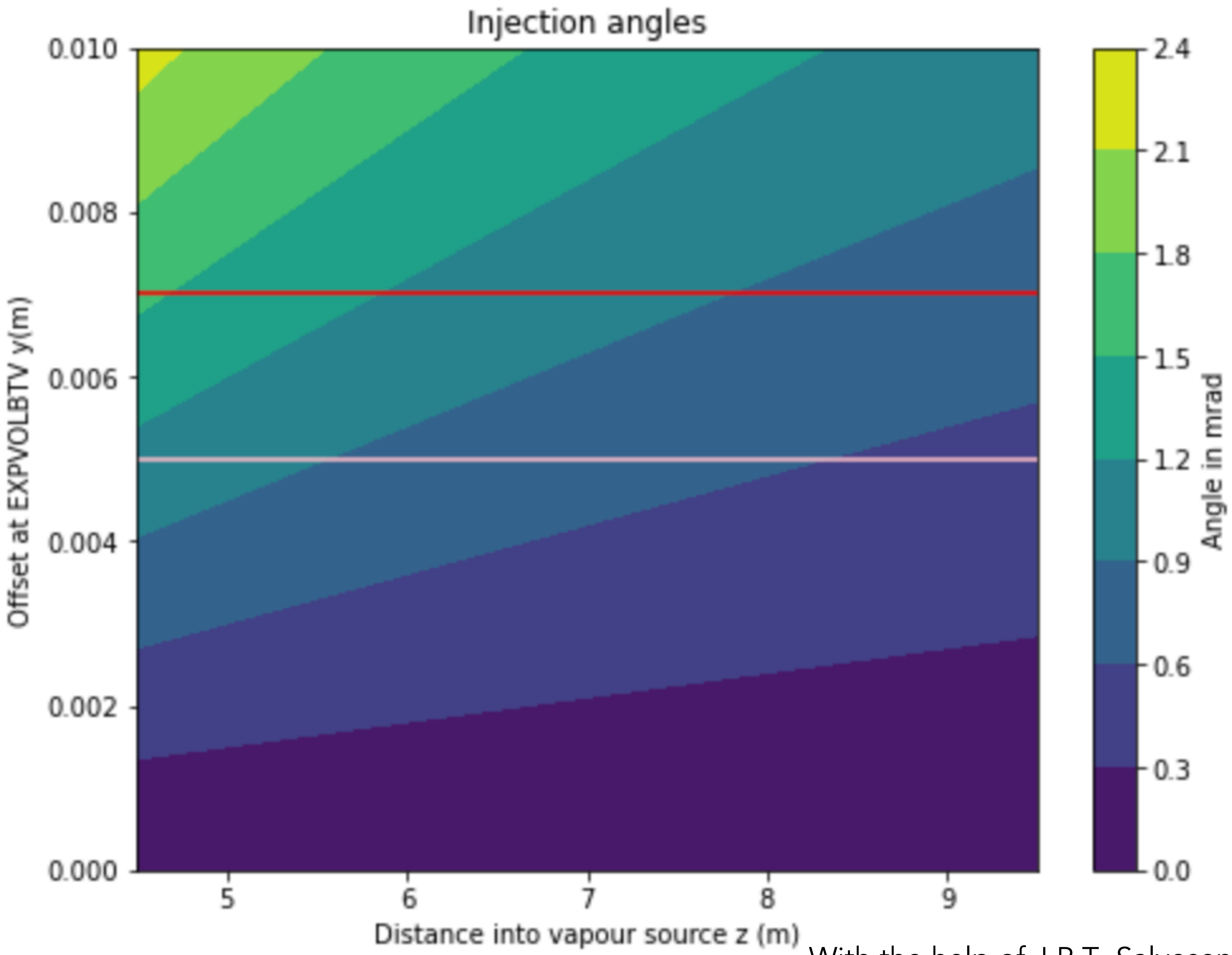
AWAKE

Estimation of injection angle and limitations for large z_e

e.g. take 2mm (two standard deviations) wide beam. In order to not have cutting at entrance => max offset 7mm (red line), 5mm max offset for beams max 4mm wide (pink line)

Angles assuming straight line trajectories (4.5m-9.5m)

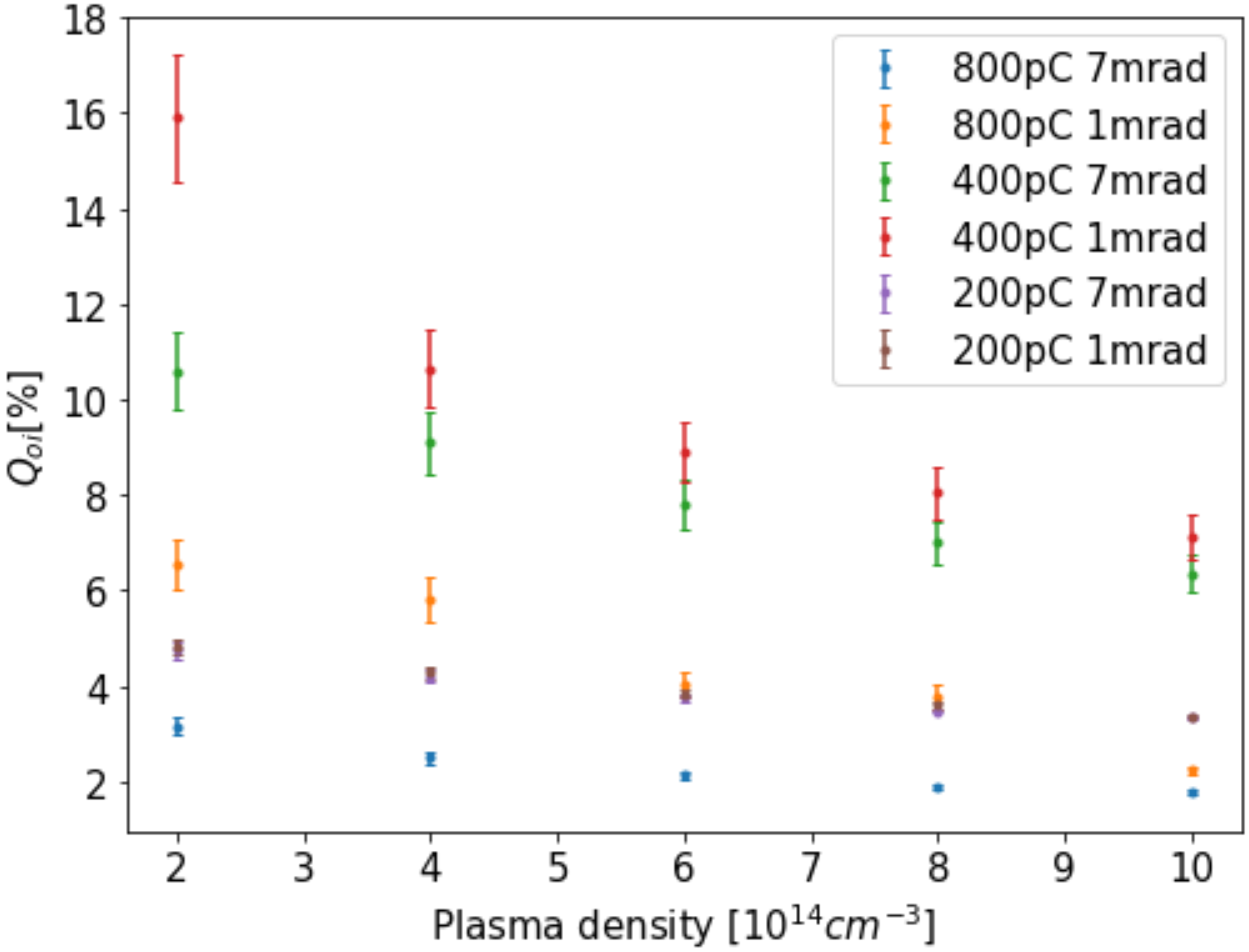
- Narrower choice, very flat injection angle up to possibly 1.2mrad for all; however not guaranteed.
- Also raises the problem of entering the plasma column before the point of injection e.g. the offset would be 1mm (~radius plasma column) 1m prior e.g. for 9.5m and this does not take beamsize into account (may enter even earlier)



With the help of J.P.T. Salvesen

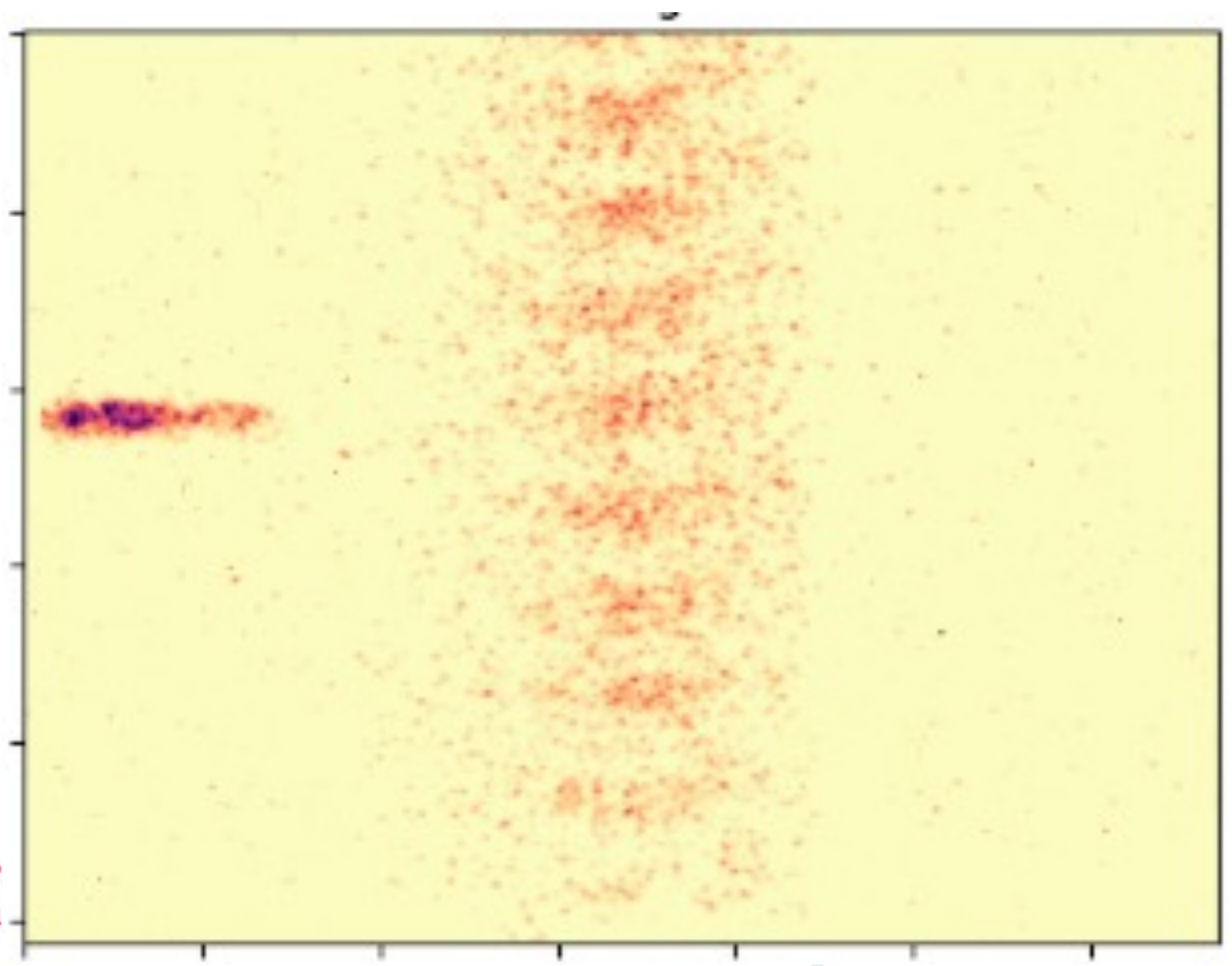
Electron beam charge overlap with wakefields

- Beam waist at 1.5m



Electron beam seeding images XMPP

2e14, 3e11, 200pC, XMPP



7e14, 1e11, 200pC, XMPP