Slice Energy Spread Measurements in the EuXFEL Injector

Stuart Walker, Sergey Tomin, Igor Zagorodnov, Nina Golubeva, Matthias Scholz, Winfried Decking, Bolko Beutner, Erion Gjonaj

LEDS Workshop 2023, Frascati, Rome, 4/10/2023

Overview

Subheading, optional

Motivation

- Uncorrelated (slice) energy spread is an important property in FELs, where high brightness is required.
- However, usually energy spread from injector is too low and must be increased using the laser heater (LH) to increase SASE performance due to the microbunching instability.
  - Ideally increased to 8 keV based on simulations from Martin Dohlus, but actual optimal value never measured.
- Regardless, understanding uncorrelated energy spread is necessary to improve machine reproducibility and understanding.
- Dynamics not understood, unable to recreate measured slice energy spread values with ASTRA simulation.

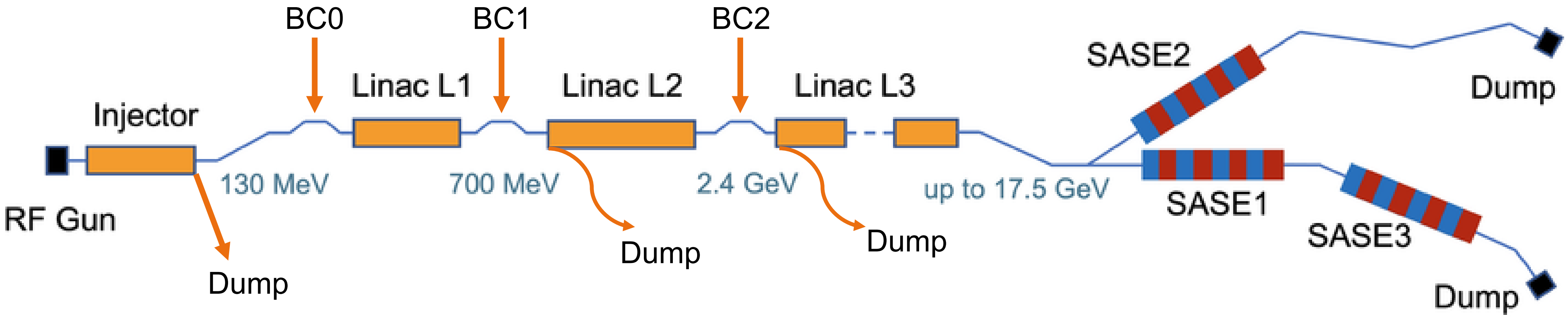
Context

- Fermi, 2020: Intrabeam scattering measured, but result highly dependent on initial energy spread, which was treated as a free parameter.
- SwissFEL, 2020: energy spread measurement in the injector using an energy scan—**15 keV** @ 200pC & >100MeV.
- EuXFEL, 2021: Similar approaching involving a dispersion scan—**6 keV** @ 250pC & 130MeV.
- PITZ, 2022: **2 keV** @ 250pC & 20MeV.
- SwissFEL, 2022: Contribution of the microbunching instability and intra-beam scattering evidenced by varying the optics -> **reduced** by adjusting optics and disabling LH chicane.
- **This talk**: recent measurements and new results since November 2022 in the **EuXFEL injector**.

The EuXFEL

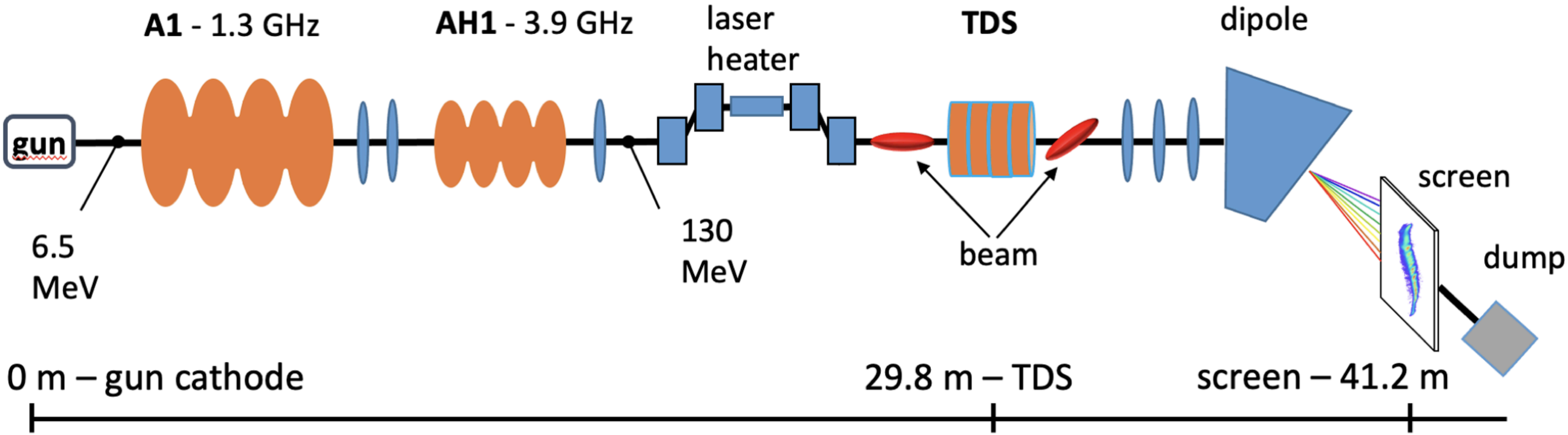
Overview

- 3.1 km machine.
- Two hard x-ray undulator lines, SA1 and SA2.
- One soft x-ray line, SA3.
- Four chicanes, laser heater chicane in injector and three for compression.
- Diagnostic stations in injector and after BC2 (at max compression).
- One transverse deflecting structure (TDS) in the injector, and one after BC2.
- Beam can be matched in diagnostic sections and just after BC1.
- Hard x-ray self-seeding in SA2, wish recent pushes to more special modes.
- Crucial to know longitudinal beam dynamics to deliver the best performance.



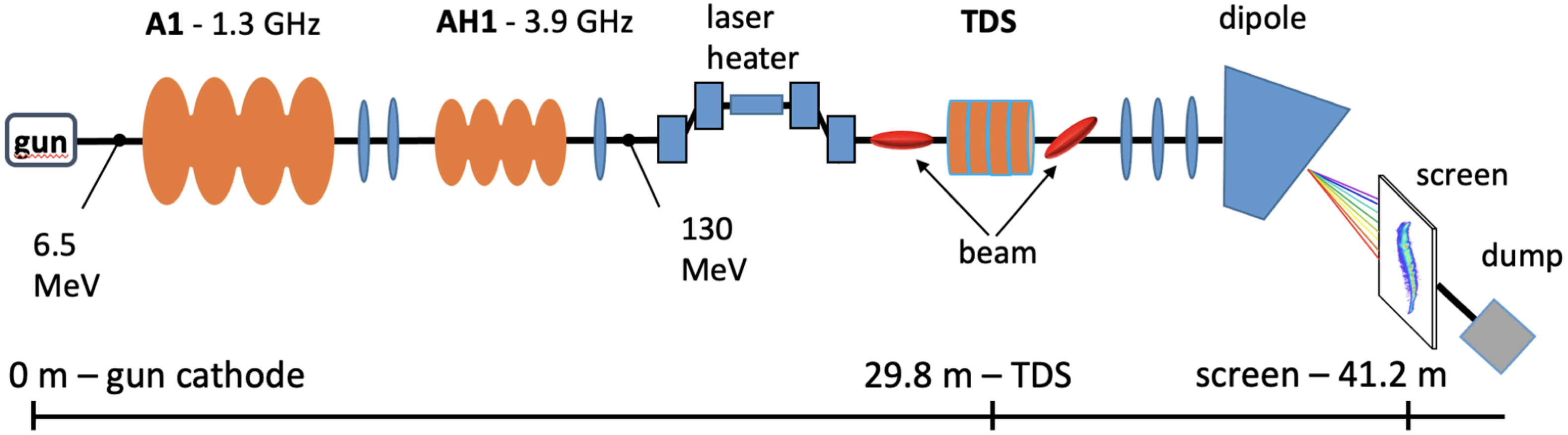
The EuXFEL

Injector



The Usual Approach

Energy Spread Measurement



Only provides an upper limit on uncorrelated spread σ_E.

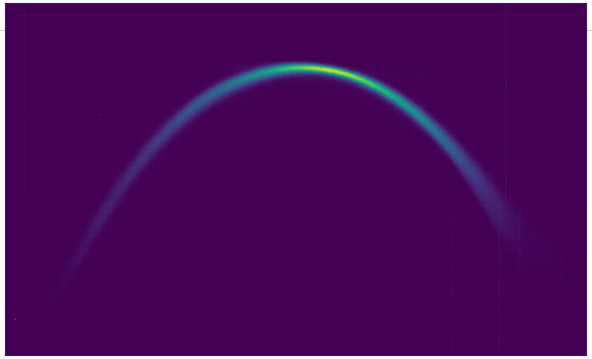
Neglected contributions to size:

- Intrinsic betatronic beam size
- TDS-induced energy spread
- Imaging resolution

In the injector these contributions can be larger than the slice energy spread's contribution!

Need to separate these effects...

Streak with TDS → Measure central slice width σ_M at local dispersion D → $\sigma_M \approx \frac{D}{E}\sigma_E$



Separating the contributions to the slice size

Energy Spread Measurement

Assuming no correlation between TDS-induced energy spread and "true" energy spread, the final slice energy spread seen at the screen:

$$\sigma_{E_{\mathrm{final}}}^2 = \sigma_E^2 + (ekV)^2\sigma_I^2$$

Beamsize in the TDS

$$\sigma_M^2 = \sigma_R^2 + \sigma_B^2 + \frac{D^2}{E^2}\sigma_E^2 + \frac{D^2}{E^2}(ekV)^2\sigma_I^2$$

Imaging resolution

Betatron

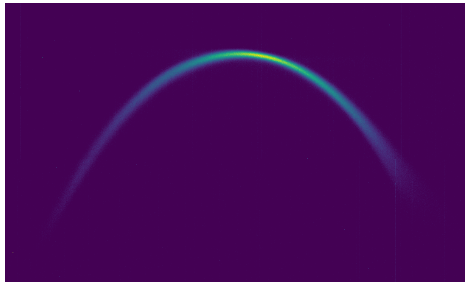
energy spread contribution

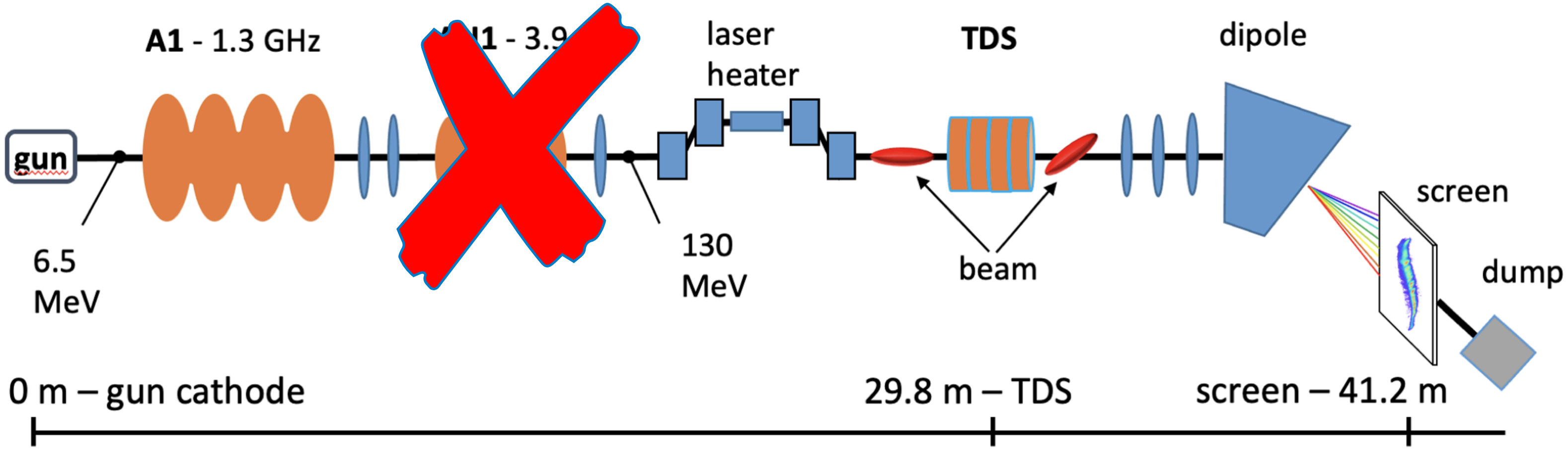
TDS contribution

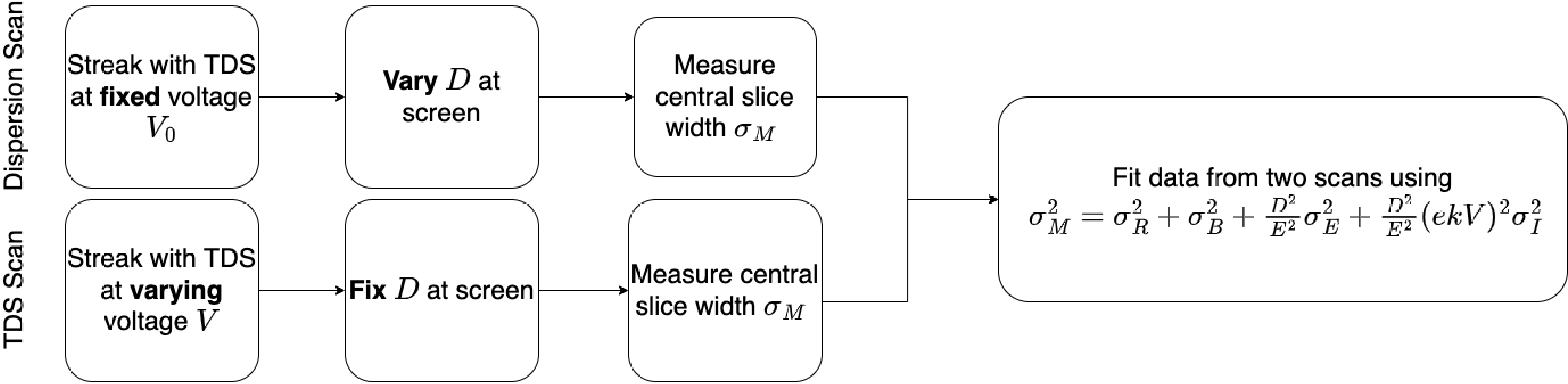
$$\sigma_B^2 = \frac{\beta_x \varepsilon_n}{\gamma_0} \qquad \sigma_I^2 = \frac{\varepsilon_n}{\gamma_0}\left(\beta_y^0 + 0.25L^2\gamma_y^0 - L\alpha_y^0\right)$$

High Resolution Technique

Energy Spread Measurement







Dispersion Scan

Streak with TDS at **fixed** voltage V_0 → **Vary** D at screen → Measure central slice width σ_M

TDS Scan

Streak with TDS at **varying** voltage V → **Fix** D at screen → Measure central slice width σ_M

Fit data from two scans using

$$\sigma_M^2 = \sigma_R^2 + \sigma_B^2 + \frac{D^2}{E^2}\sigma_E^2 + \frac{D^2}{E^2}(ekV)^2\sigma_I^2$$

Derived Values

Energy Spread Measurement

For the two scans:

$$\sigma_M^2 = \sigma_R^2 + \sigma_B^2 + \frac{D^2}{E^2}\sigma_E^2 + \frac{D^2}{E^2}(ekV)^2\sigma_I^2$$

$$\sigma_M^2 = A_V + B_V V^2 \qquad \sigma_M^2 = A_D + B_D D^2$$

$$A_V = \sigma_R^2 + \sigma_B^2 + \frac{D^2}{E^2}\sigma_E^2$$

$$B_V = \frac{D^2}{E^2}(ek)^2\sigma_I^2$$

$$A_D = \sigma_R^2 + \sigma_B^2$$

$$B_D = \frac{1}{E^2}\sigma_E^2 + \frac{1}{E^2}(ekV)^2\sigma_I^2$$

$$\sigma_E = \frac{E_0}{D_0}\sqrt{A_V - A_D}$$

$$\sigma_I = \frac{E_0}{D_0 ek}\sqrt{B_V}$$

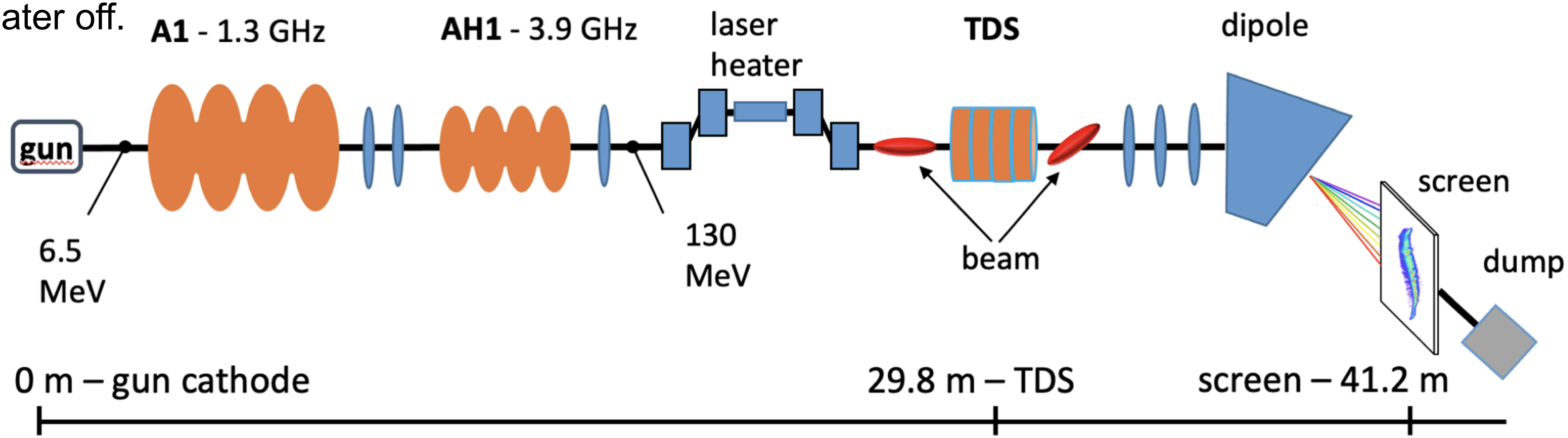
$$\sigma_B = \sqrt{B_\beta \beta_x^0}$$

$$B_\beta = \sigma_I^2(\beta_y^0 + 0.25L^2\gamma_y^0 - L\alpha_y^0)^{-1}$$

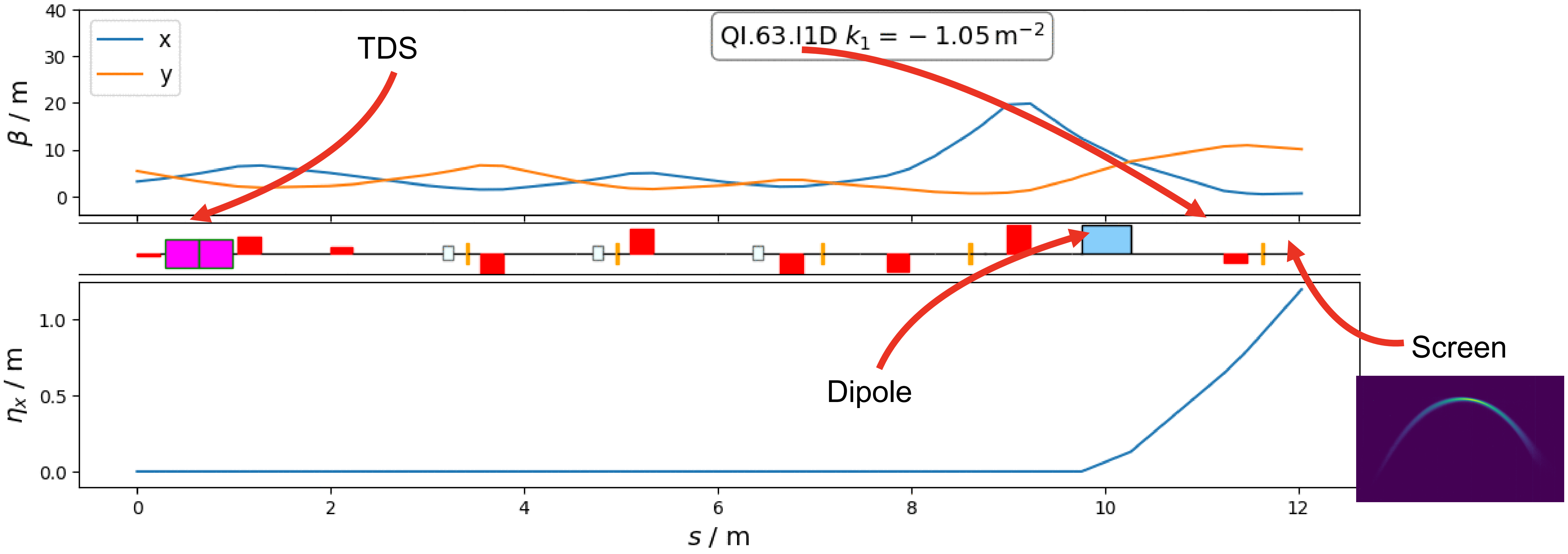
$$\sigma_R = \sqrt{A_D - \sigma_B^2}$$

Injector Setup

- Calibrate the gun phase.
- Turn off AH1 for minimum chirp contribution to energy spread.
- Go on crest in A1, adjust the voltage so we are at 130 MeV at the screen.
- Turn the laser heater off.
- Apply **special optics** to maximise the ratio of the dispersion to the betatron contributions to the spot size.
- Match the central slice.
- Measure the dispersion.



Special optics for measurement from TDS to the screen



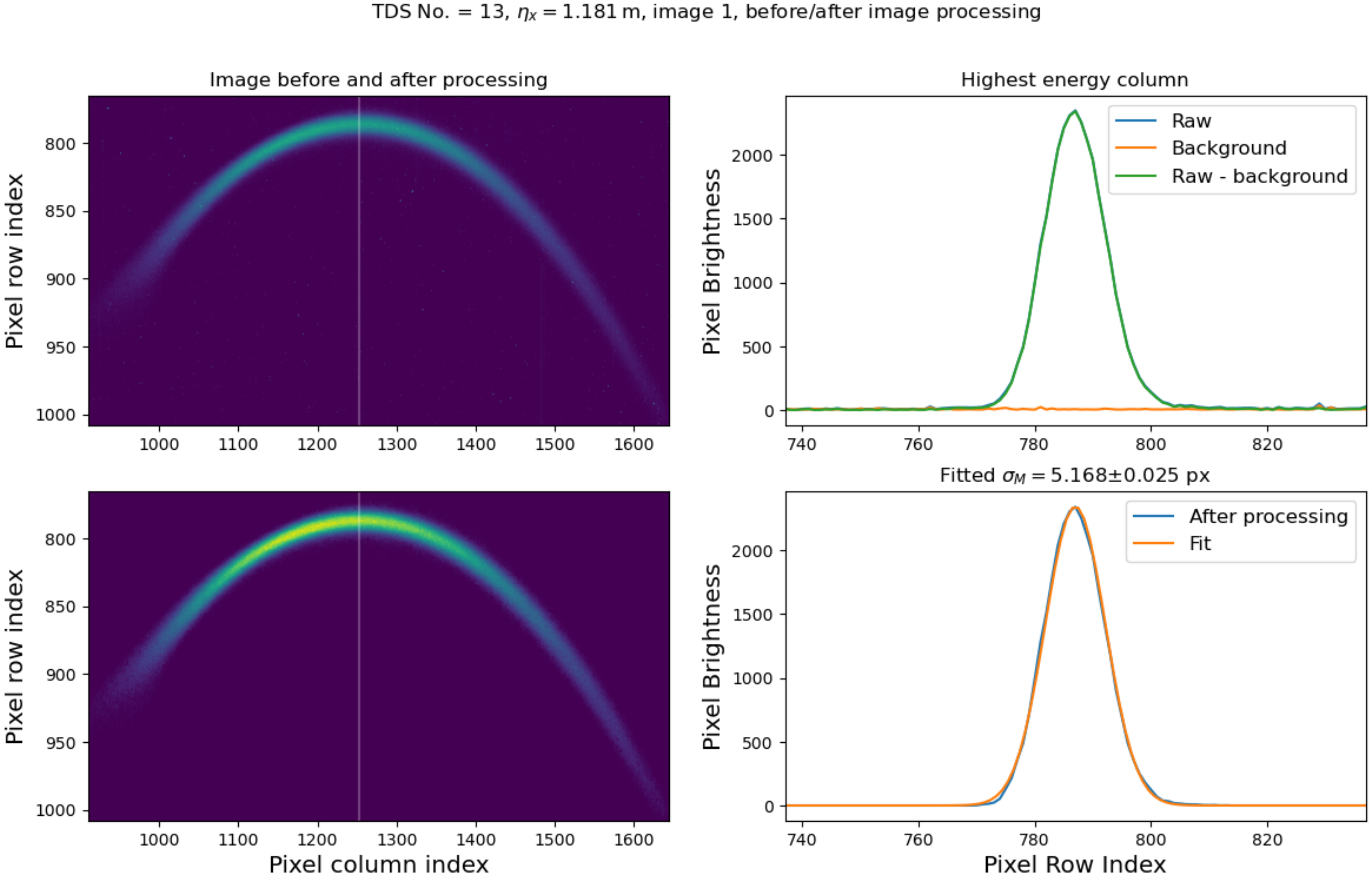
Procedure

Take 5 background images at the start of the measurement, and then 30 images:

1. At each TDS ***V*** in the voltage scan.
2. At each D_x at the screen in dispersion scan.
3. At each β_x at the screen in the beta scan.

Then:

1. Subtract background.
2. Mask to remove isolated blobs.
3. Pick the largest connected non-zero pixel blob to be "the beam".
4. Fit a Gaussian to 10 slices centred on highest energy slice & average.



28th November 2022 Measurements

- Aim:
  - Repeat measurement from 2021 publication (σ_E = 5.9 keV).
  - Match beamline configuration from that time as much as possible.
  - Particular attention to:
    - Gun gradient: 54.7 MV/m.
    - Solenoid: 326 A.
  - **Cathode changed in 2022!**

Outcome:

- Three energy spread measurements over 8 hours:
  1. Gun gradient 54.7 MV/m, solenoid 326 A, gun phase -43° (most similar to 2021 result).
  2. Gun gradient to 56.5 MV/m, solenoid to 336 A.
  3. Solenoid to 335 A, gun phase to -41°.

Results

Scenario	σ_E / keV	Solenoid / A	Gun Gradient / MV m^{-1}	Gun Phase / °
Feb. 2021 Published Result	5.842	338	56.7	-42.9
Nov. 2022 Measurement 1	4.313	326.6	54.7	-43.1
Nov. 2022 Measurement 2	3.635	336	56.5	-43.6
Nov. 2022 Measurement 3	3.385	335	56.5	-41.6

Variable	Feb. 2021	Nov. 2022	Unit
A_V	4.530×10^{-9}	3.043×10^{-9}	m^2
B_V	1.515×10^{-21}	1.326×10^{-21}	$\mathrm{m}^2\,\mathrm{V}^{-2}$
A_D	1.702×10^{-9}	1.540×10^{-9}	m^2
B_D	2.433×10^{-9}	1.416×10^{-9}	-
σ_E	5.8	4.3	keV
σ_I	68.0	64	µm
σ_B	29	28	µm
σ_R	28	27	µm
ε_n	0.38	0.34	mm · mrad
V_0	0.61	–0.63	MV
D_0	1.183	1.169	m

$$\sigma_M^2 = \sigma_R^2 + \sigma_B^2 + \frac{D^2}{E^2}\sigma_E^2 + \frac{D^2}{E^2}(ekV)^2\sigma_I^2$$

Nov. 2022 Measurements:

1. Gun gradient 54.7 MV/m, solenoid 326 A, gun phase -43° (most similar to 2021 result)
2. Gun gradient to 56.5 MV/m, solenoid to 336 A,
3. Solenoid to 335 A, gun phase to -41°.

Imperfect recreation of 2021 conditions, was as close as we could get.

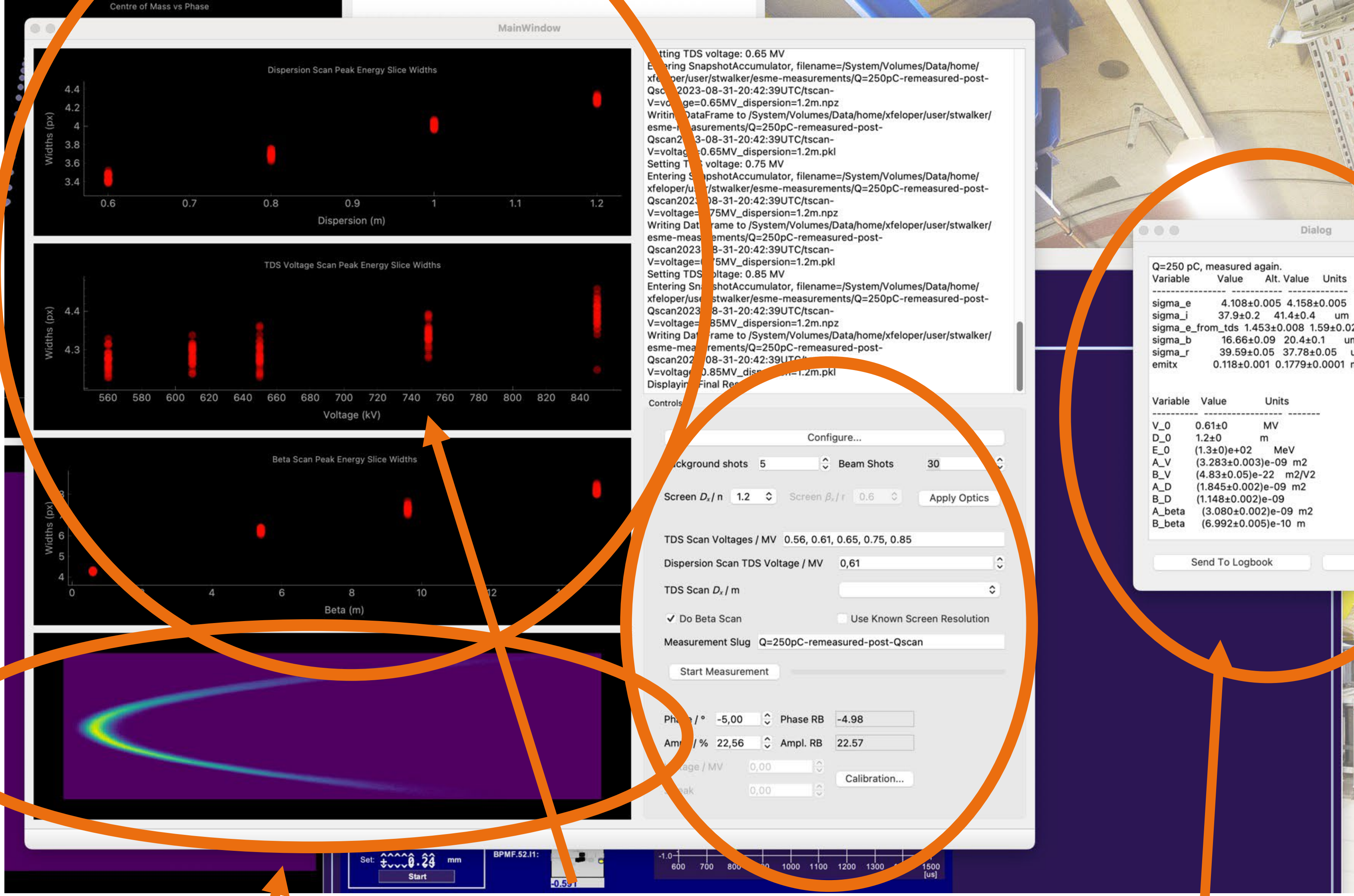
Comments

- The measured energy spread in the injector decreased since Feb. 2021 **from 5.9 keV to 4.2 keV**.
  - Through 2023 has since remained stabled at around **4 keV** with repeated measurements.
- Still not the value predicted by theory (Erion's simulations predict ≈ 3 keV with IBS).
- In the period between these two measurements:
  - The cathode has changed.
  - The bunch length was increased from around 4 ps to around 5 ps.
- Suggests a long term drift in the energy spread.
- These three datapoints took eight hours to acquire.

New Tooling

Measurement

- Taking ~400 images across ~15 machine setpoints without special tooling would take about an hour. Then, offline analysis takes another 10 minutes.
- To this end we have developed a GUI to do the parameter scanning.
    - Live image processing panel.
    - Live slice width scan plots (e.g. TDS voltage against central slice width).
    - Immediate results at the end of the scan.
- **Bottom line: results in a few minutes.**



```
tting TDS voltage: 0.65 MV
E  ering SnapshotAccumulator, filename=/System/Volumes/Data/home/
xfe  per/user/stwalker/esme-measurements/Q=250pC-remeasured-post-
Qsc  2023-08-31-20:42:39UTC/tscan-
V=vo  ge=0.65MV_dispersion=1.2m.npz
Writin  DataFrame to /System/Volumes/Data/home/xfeloper/user/stwalker/
esme-  asurements/Q=250pC-remeasured-post-
Qscan2  3-08-31-20:42:39UTC/tscan-
V=voltag  0.65MV_dispersion=1.2m.pkl
Setting T  voltage: 0.75 MV
Entering S  apshotAccumulator, filename=/System/Volumes/Data/home/
xfeloper/u  /stwalker/esme-measurements/Q=250pC-remeasured-post-
Qscan202  08-31-20:42:39UTC/tscan-
V=voltage=  75MV_dispersion=1.2m.npz
Writing Dat  rame to /System/Volumes/Data/home/xfeloper/user/stwalker/
esme-meas  ements/Q=250pC-remeasured-post-
Qscan2023  8-31-20:42:39UTC/tscan-
V=voltage=  75MV_dispersion=1.2m.pkl
Setting TDS  oltage: 0.85 MV
Entering Sn  shotAccumulator, filename=/System/Volumes/Data/home/
xfeloper/use  stwalker/esme-measurements/Q=250pC-remeasured-post-
Qscan2023  8-31-20:42:39UTC/tscan-
V=voltage=  85MV_dispersion=1.2m.npz
Writing Dat  Frame to /System/Volumes/Data/home/xfeloper/user/stwalker/
esme-mea  rements/Q=250pC-remeasured-post-
Qscan202  08-31-20:42:39UTC/
V=voltag  0.85MV_dis  n=1.2m.pkl
Displayin  Final Re
```

ckground shots 5 Beam Shots 30

Screen D_x / n 1.2 Screen β_x / r 0.6

TDS Scan Voltages / MV 0.56, 0.61, 0.65, 0.75, 0.85

Dispersion Scan TDS Voltage / MV 0,61

TDS Scan D_x / m

☑ Do Beta Scan ☐ Use Known Screen Resolution

Measurement Slug Q=250pC-remeasured-post-Qscan

Ph e / ° -5,00 Phase RB -4.98

Am / % 22,56 Ampl. RB 22.57

age / MV 0,00

eak 0,00

```
Q=250 pC, measured again.
Variable          Value       Alt. Value     Units
----------------  -----------  -------------
sigma_e          4.108±0.005  4.158±0.005
sigma_i          37.9±0.2     41.4±0.4       um
sigma_e_from_tds 1.453±0.008  1.59±0.02
sigma_b          16.66±0.09   20.4±0.1       un
sigma_r          39.59±0.05   37.78±0.05     u
emitx            0.118±0.001  0.1779±0.0001  r


Variable   Value               Units
---------- ------------------- --------
V_0        0.61±0              MV
D_0        1.2±0               m
E_0        (1.3±0)e+02         MeV
A_V        (3.283±0.003)e-09   m2
B_V        (4.83±0.05)e-22     m2/V2
A_D        (1.845±0.002)e-09   m2
B_D        (1.148±0.002)e-09
A_beta     (3.080±0.002)e-09   m2
B_beta     (6.992±0.005)e-10   m
```

Slice widths

Post-processed image

Measurement control

Measurement result

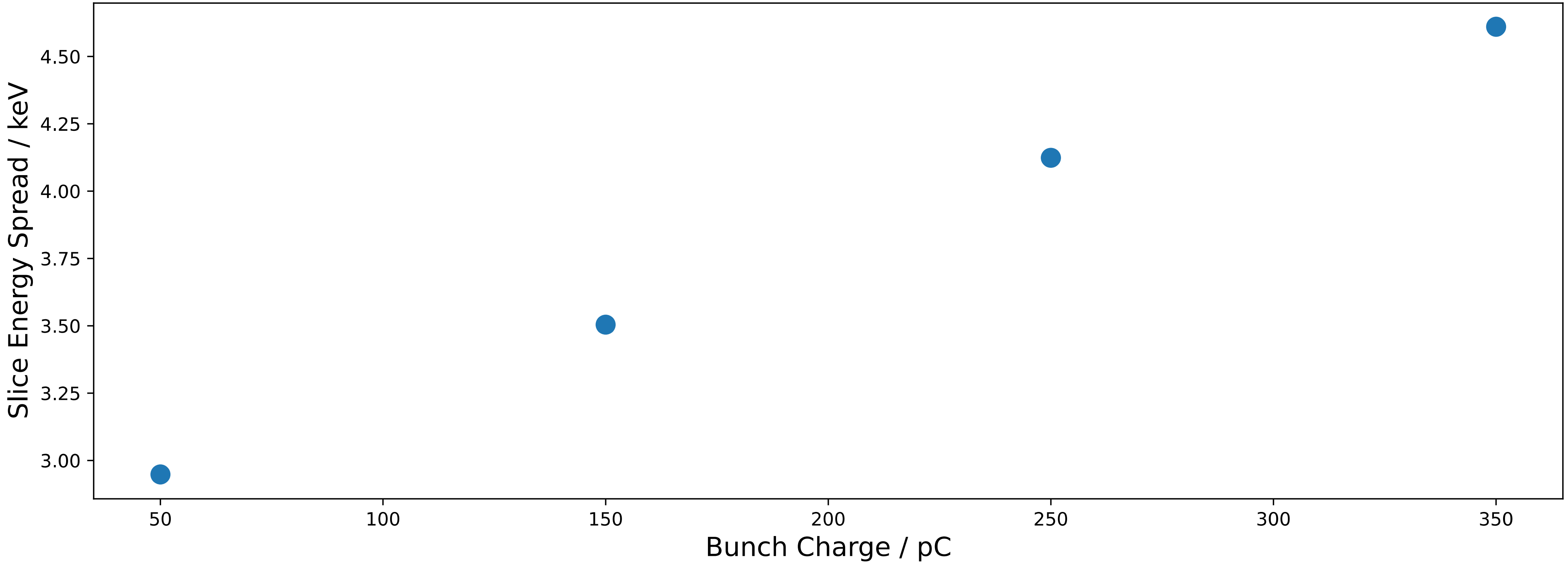
New Scans

- We did two scans over a single four hour shift on 31st August 2023.
  - Bunch charge scan: 50 pC, 150 pC, 250 pC and 350 pC.
  - Laser heater chicane R_{56} scan: -1 mm, -2.5 mm, -4.336 mm (nominal), -5.5 mm and -7 mm.
- We rematched the projected emittance every single time,
  - then **measured** the central slice emittances (showing good matching already).
- We additionally scanned the beta function at the screen (not shown here).
- The fast measurement software described previously allows us to do these sorts of scans now.

Bunch Charge Scan

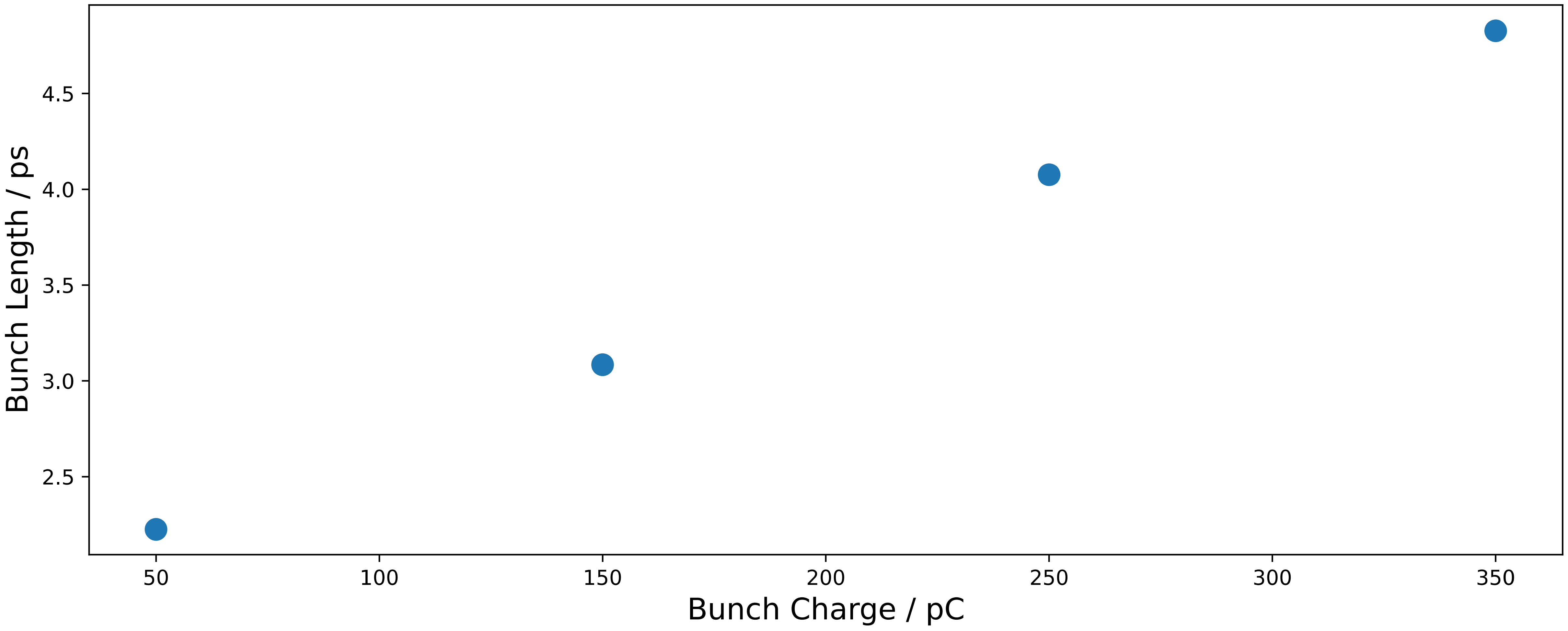
Slice Energy Spreads

- We scanned from 50 pC to 350 pC in steps of 100 pC.
- Unable to resolve the TDS contribution to the energy spread at 50 pC, so assumed to be zero.
  - No obvious reason to consider energy spread from TDS to be zero, related to the camera sensitivity?



Bunch Charge Scan

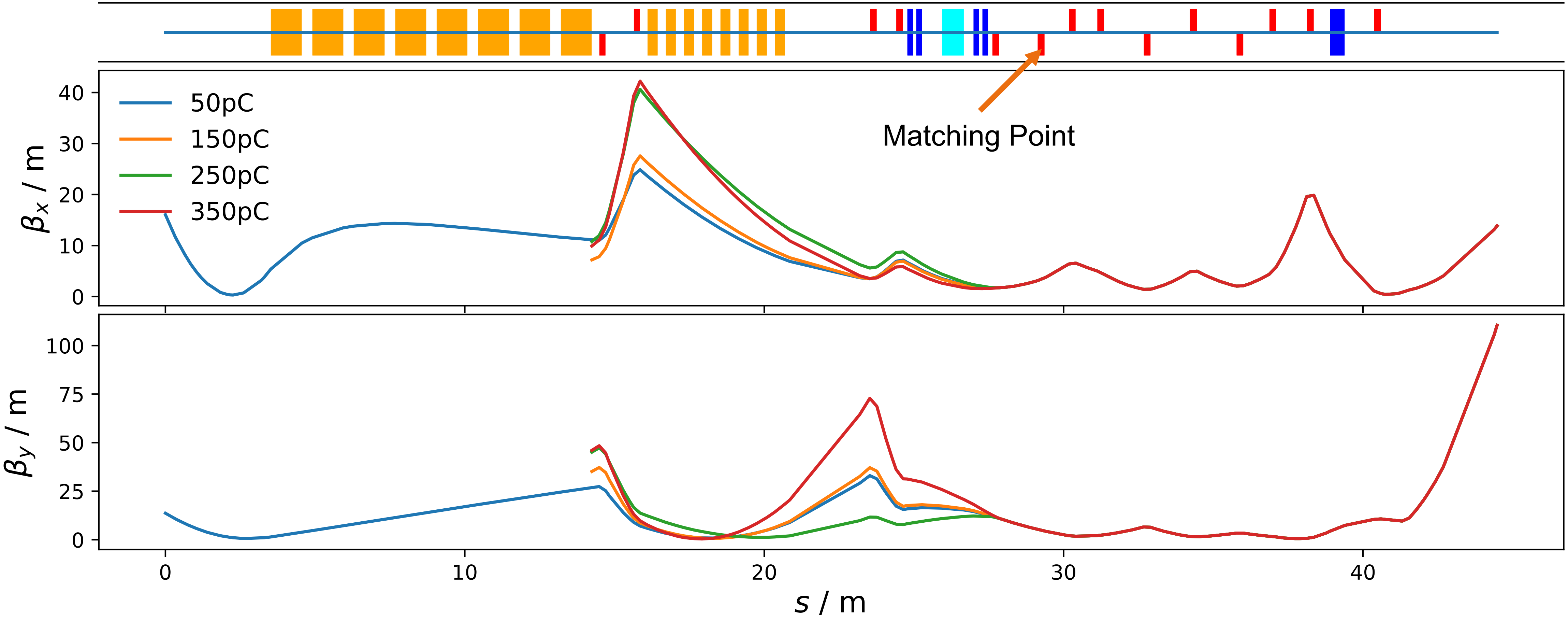
Bunch Lengths



Bunch Charge Scan

Transverse Optics

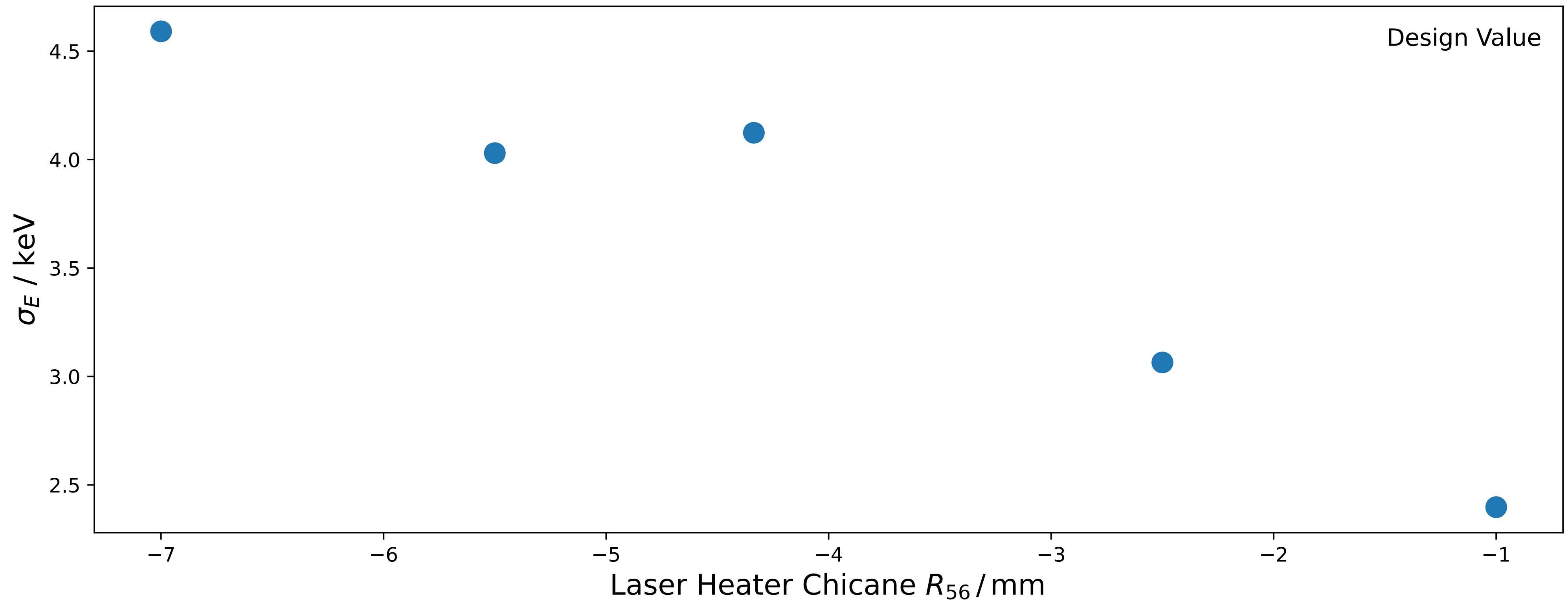
- $D_x = 1.2$ m at the screen.
- Only 50 pC backtracked to cathode due to reduced space charge effects at this charge.



Laser Heater Chicane R_{56} Scan

Slice Energy Spreads

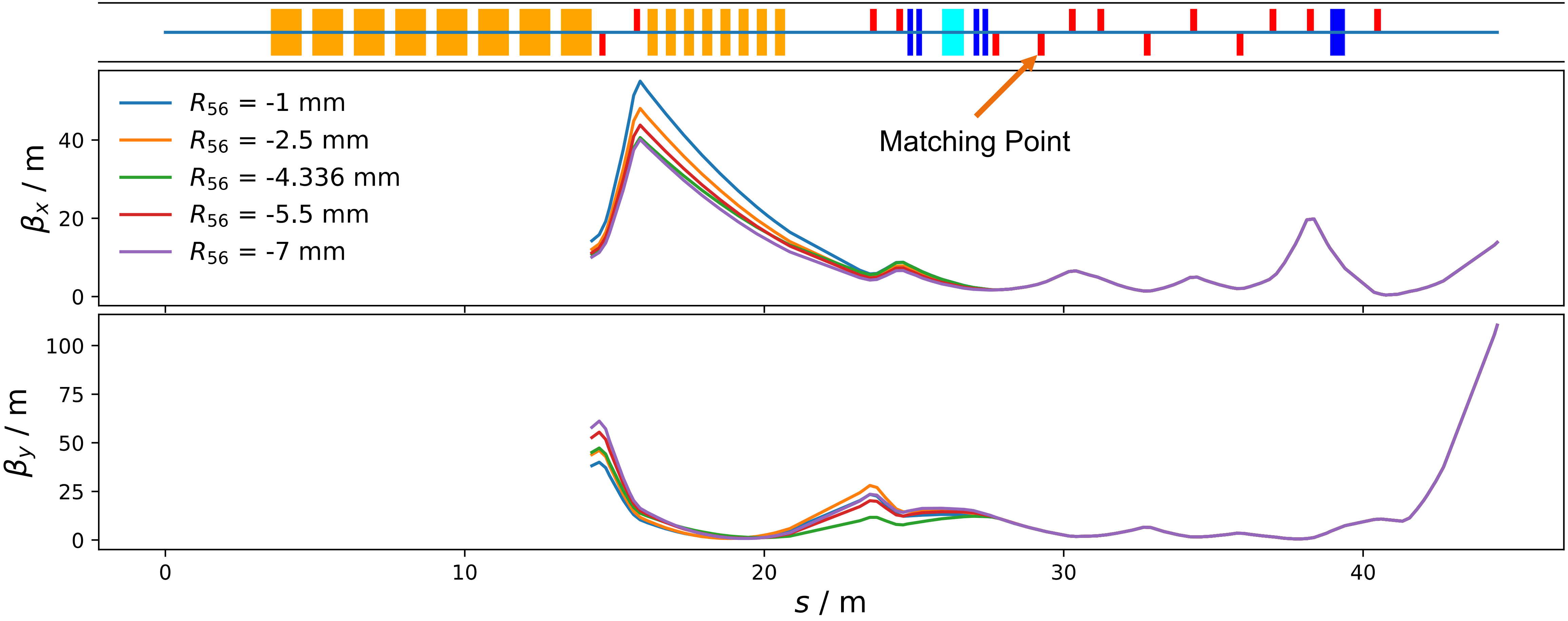
- We scanned the R_{56} of the laser heater chicane from -7 mm to -1 mm (the minimum) @ Q = 250 pC.
- We rematched the beam each time, and then measured the central slice (good matching).
- Design setting (-4.336 mm) not scanned in order with the other setpoints.
- Strong dependence on LH R_{56} is apparent, from 4.5 keV at maximum to 2.4 keV at minimum.



Laser Heater Chicane R_{56} Scan

Transverse Optics

- D_x = 1.2m at the screen.
- 250 pC, so backtracked only to first cavity.



Conclusion

- The slice energy spread shows wide tunability based on the charge and laser heater chicane R_{56}:
  - (2.4–4.6) keV from -1 mm to -7 mm R_{56} @ 250 pC.
  - (3.0–4.5) keV from 50 pC to 350 pC @ nominal R_{56}.
- This, in combination with the longer term decrease from 6 keV to 4 keV in the last two years for unknown reasons, makes it clear that there is still a lot to be understood about the longitudinal phase space dynamics in the injector.
- Important to understand to boost reproducibility.
- The charge scan points at possible IBS contributions to the slice energy spread.
- The R_{56} dependence needs more understanding and explanation. MBI?
- We now have a fast and easy to use data taking and online analysis tool which gives immediate results. Room for further studies of other parameters, e.g. bunch length.

Outlook

- Upcoming experiment in October for additional chicane studies (opening the undulator and repeating).
- We want to go to 10 pC to neglect collective effects and try to directly observe the thermal slice energy spread from the cathode.
- Aiming to take part in the upcoming new laser commissioning—-bunch length scans (not possible with current laser).
- We would like to provide an absolute calibration of the laser heater.
- IBS simulation work ongoing with Erion Gjonaj to ground these results more in theory.
- Further work on the GUI and tooling to improve usability and speed.
- New measurements and studies are possible with new software—open to ideas, suggestions and collaboration!
- We want to ultimately transport to the in BC2 and measure there at 130 MeV—tricky for a number of reasons.

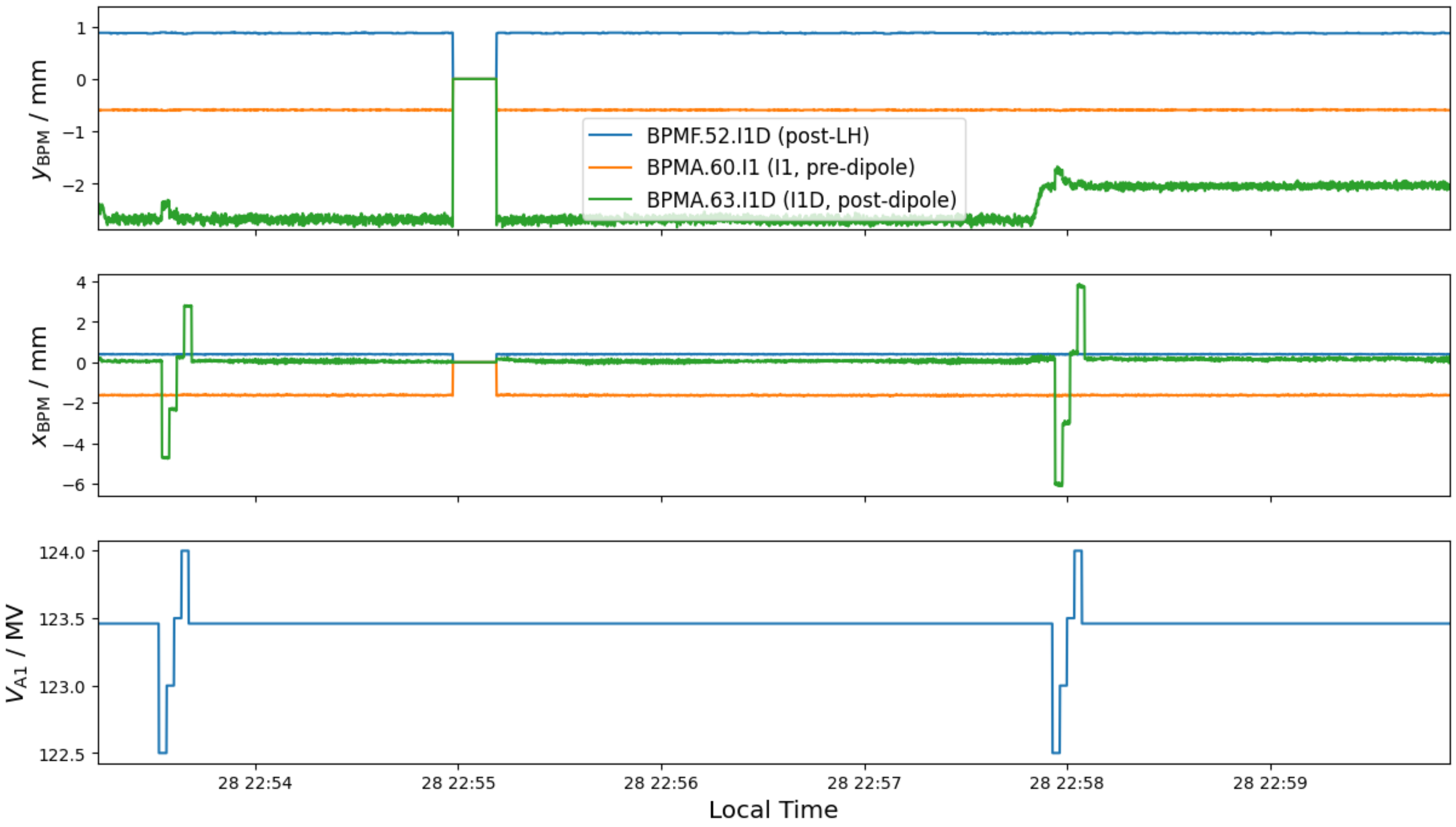
Thank you
Vielen Dank

Contact

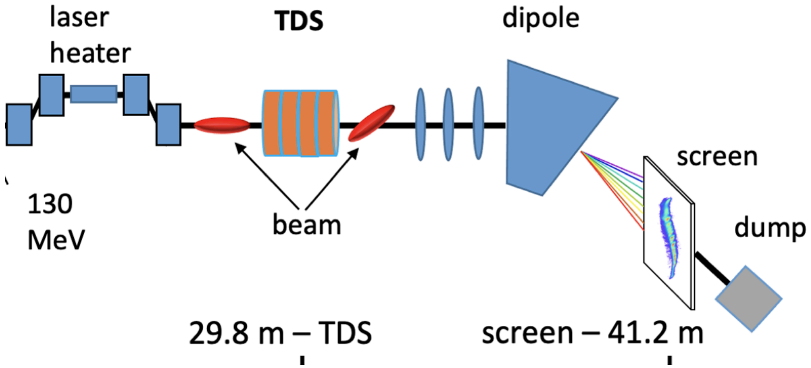
Deutsches Elektronen-Synchrotron DESY	Stuart Walker MXL stuart.walker@desy.de
www.desy.de	4756

Backup

Do we get a kick from A1 when measuring the dispersion?



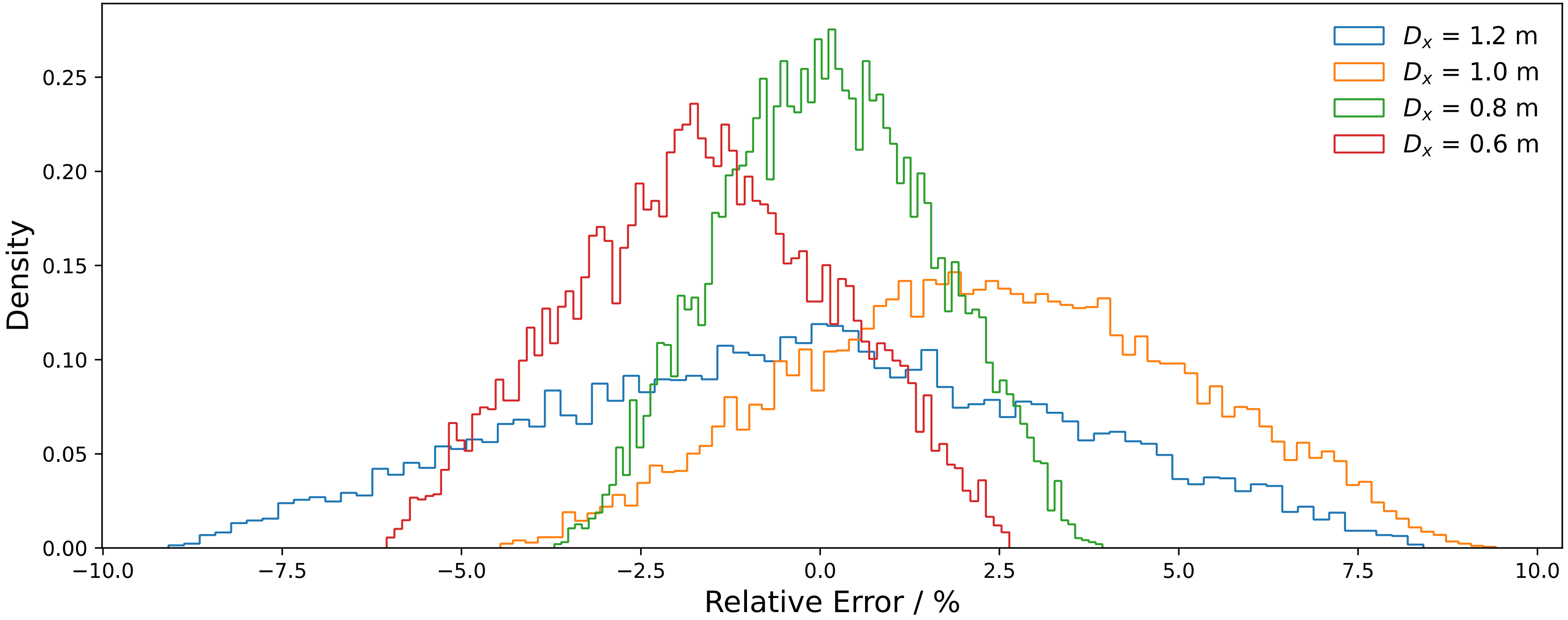
Measurement at lowest dispersion (~0.6m) followed by at highest dispersion (1.1m).



Possible Dispersion Leakage from the LH Chicane

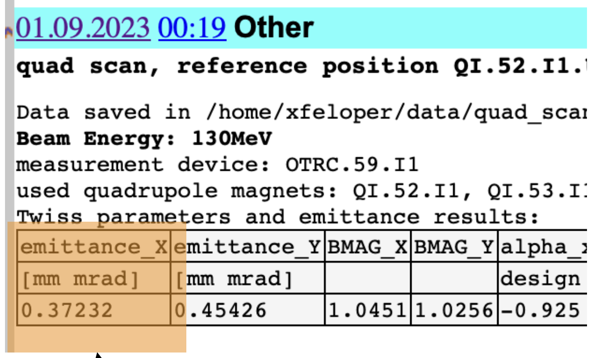
- We did not remeasure the dispersion at each setpoint of the laser heater R_{56} scan.
  - Possible: we have some leaked dispersion from the chicane at the screen.
- First two dipoles have same power supplies, second two are each independent.
- Consider: Identical 15% error in first two dipoles and independent 15% errors in second pair, perhaps some sort of ”worst case”.

- Simulated in OCELOT.
- Dispersion at the screen is tolerant to even large changes in the LH dipoles.
- Nevertheless should measure the dispersion in future experiments.
- Translates max ±10% error in energy spread.



Emittance Measurements

- Matthias matching/measurement tool is vital to our measurement.
- We match projected and then measure slice—and normally this gives reasonable matching, but we extract much smaller emittances from our scans.
- We see measured central slice emittances that are larger than the corresponding projected emittances even with apparently ”good” matching.
- Is there any way we can reduce the error bars here?



01.09.2023 00:19 **Other**

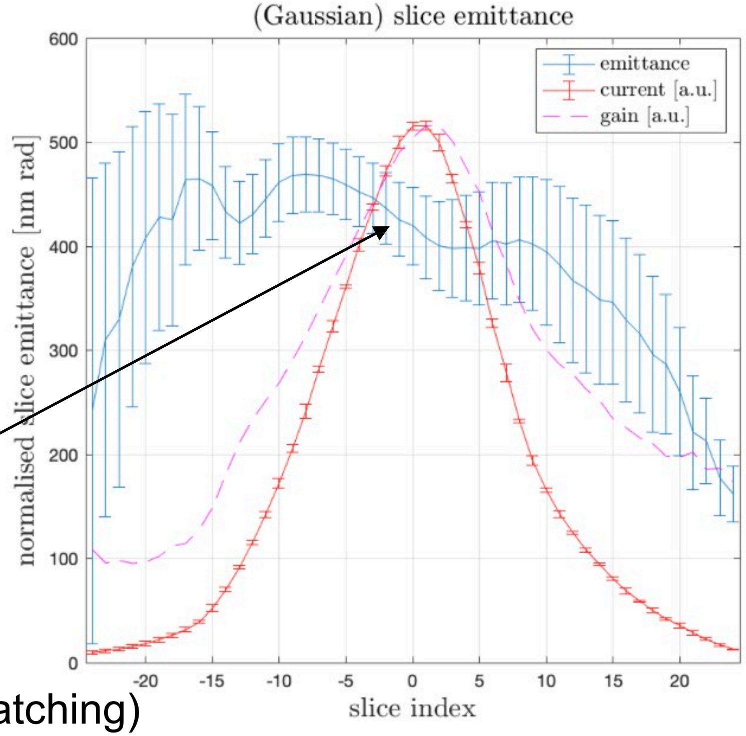
quad scan, reference position QI.52.I1.

Data saved in /home/xfeloper/data/quad_sca
Beam Energy: 130MeV
measurement device: OTRC.59.I1
used quadrupole magnets: QI.52.I1, QI.53.I
Twiss parameters and emittance results:

emittance_X	emittance_Y	BMAG_X	BMAG_Y	alpha_
[mm mrad]	[mm mrad]			design
0.37232	0.45426	1.0451	1.0256	-0.925

Projected

Central slice (0.45 mm•mrad)
measured a minute later (no matching)

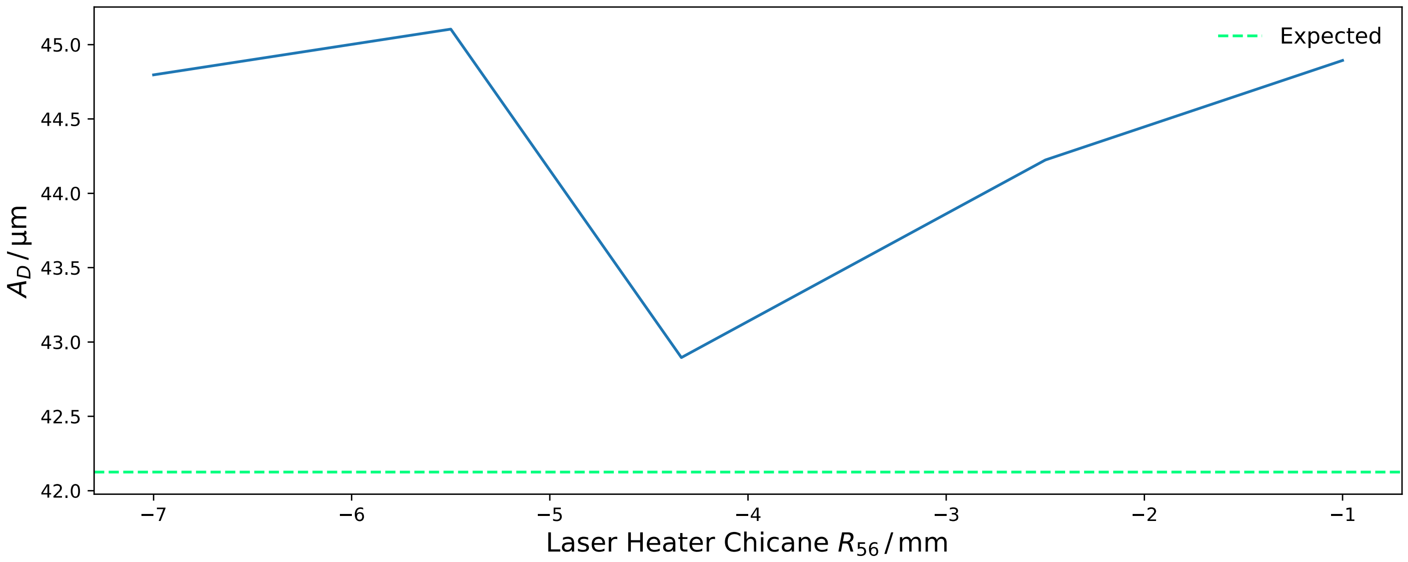


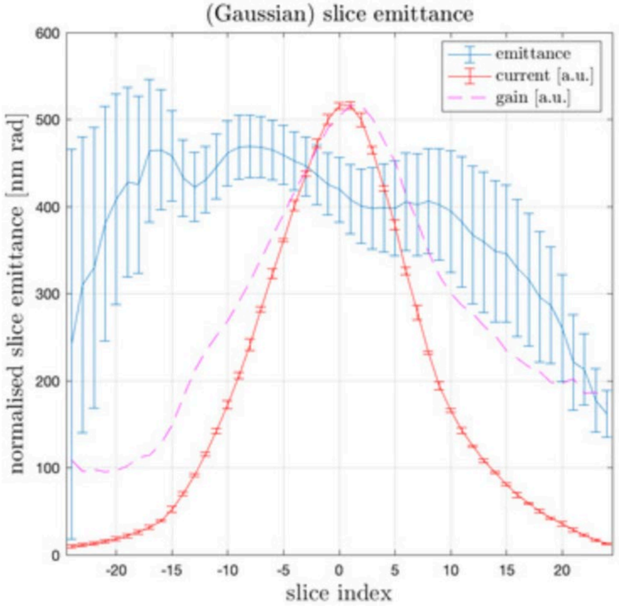
ref

Constant Contributions to Measured Widths

$$A_D = \sigma_R^2 + \sigma_B^2$$

- In principle both are known:
  - Screen resolution *(σ_R)* from dedicated optics simulations (Artem)
  - Betatron contribution (σ_B) from slice emittance measurement and linear optics (Matthias)
- σ_R = 28µm (from Artem and previous scans); β_x = 0.6 m and ε_x = 0.43 mm•mrad (Matthias matching tool)
- Constant terms remain constant across the scan, but ~7% larger than expected (from Matthias+Artem).





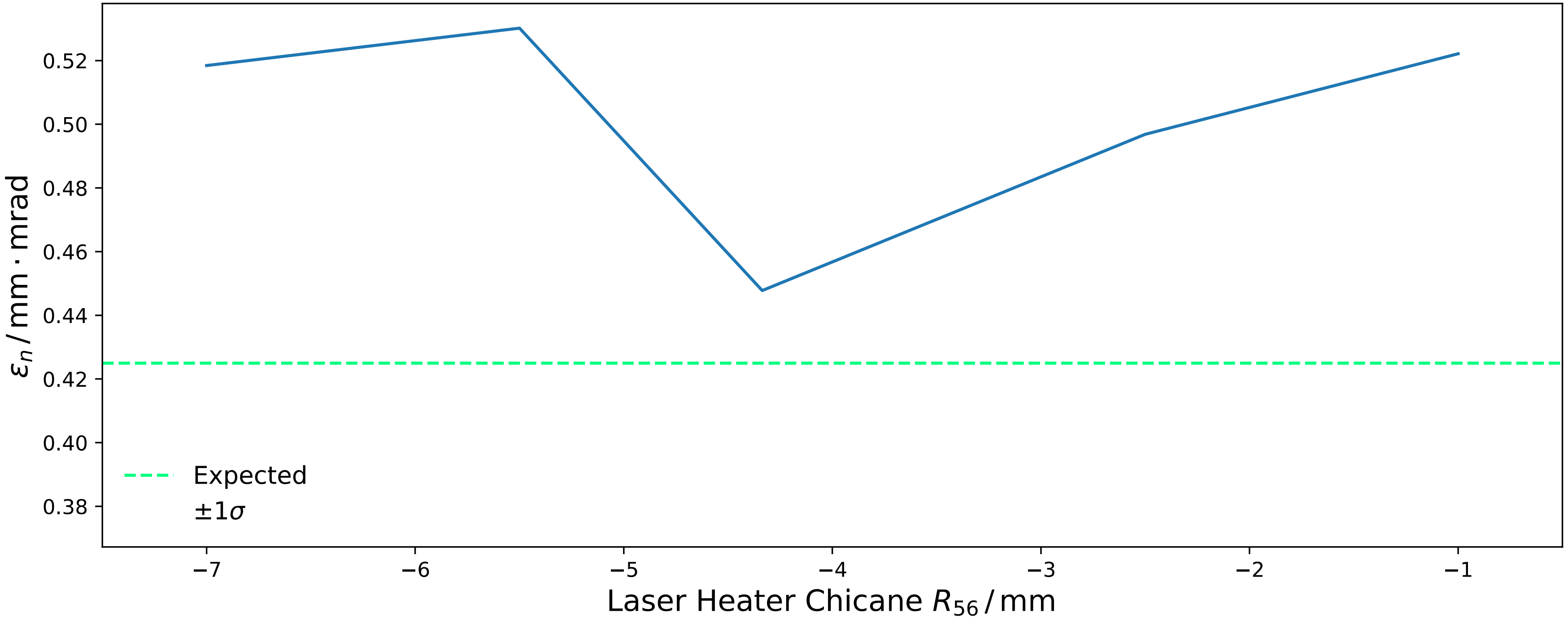
The Matthias Tool

Deriving the emittance assuming the screen resolution

- Fitting A_D and using a pre-calculated value of σ_R, we can extract a value for the slice emittance.
- We independently measure, using Matthias' matching tool, (0.43±0.05) mm•mrad for the slice emittance.

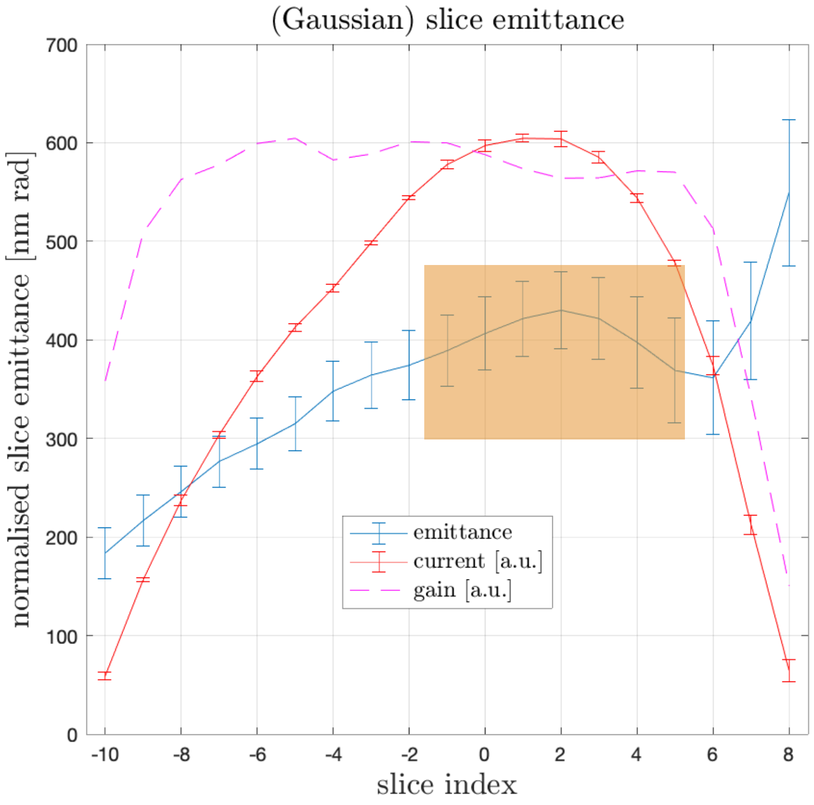
$$\varepsilon_n = \frac{\gamma_0}{\beta_x}\left(A_D - \sigma_R^2\right)$$

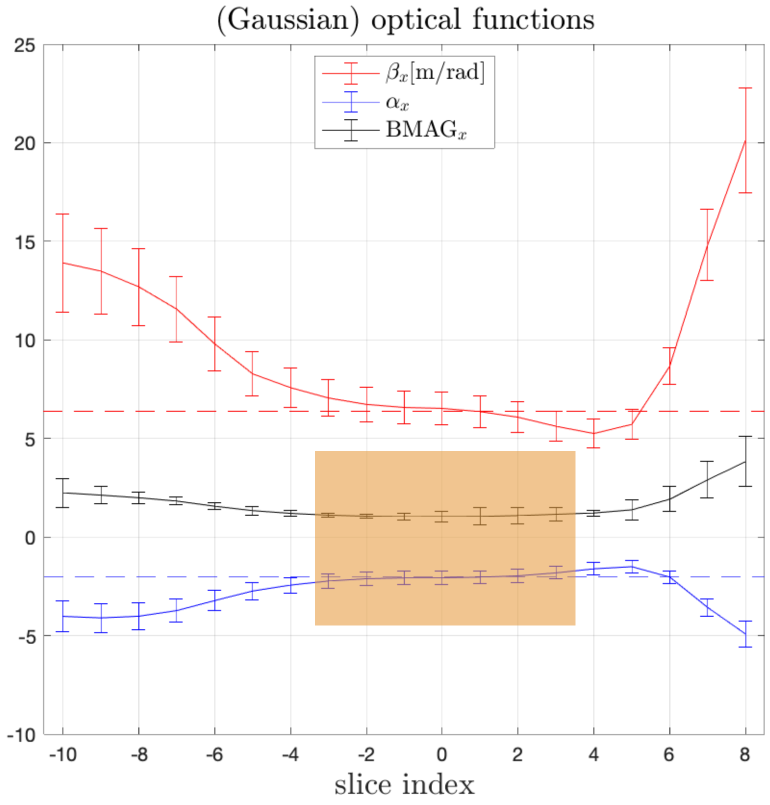
- Not entirely in disagreement with our derived value.
- Can we reduce the uncertainties in the emittance measurement?



Beam Matching

- Central slice always matched for measurements
  - Very important, otherwise can get an artificially deflated energy spread result!
  - Use screen just in front of TDS
- We remeasured the dispersion at every single point in the dispersion scan and once per TDS scan.

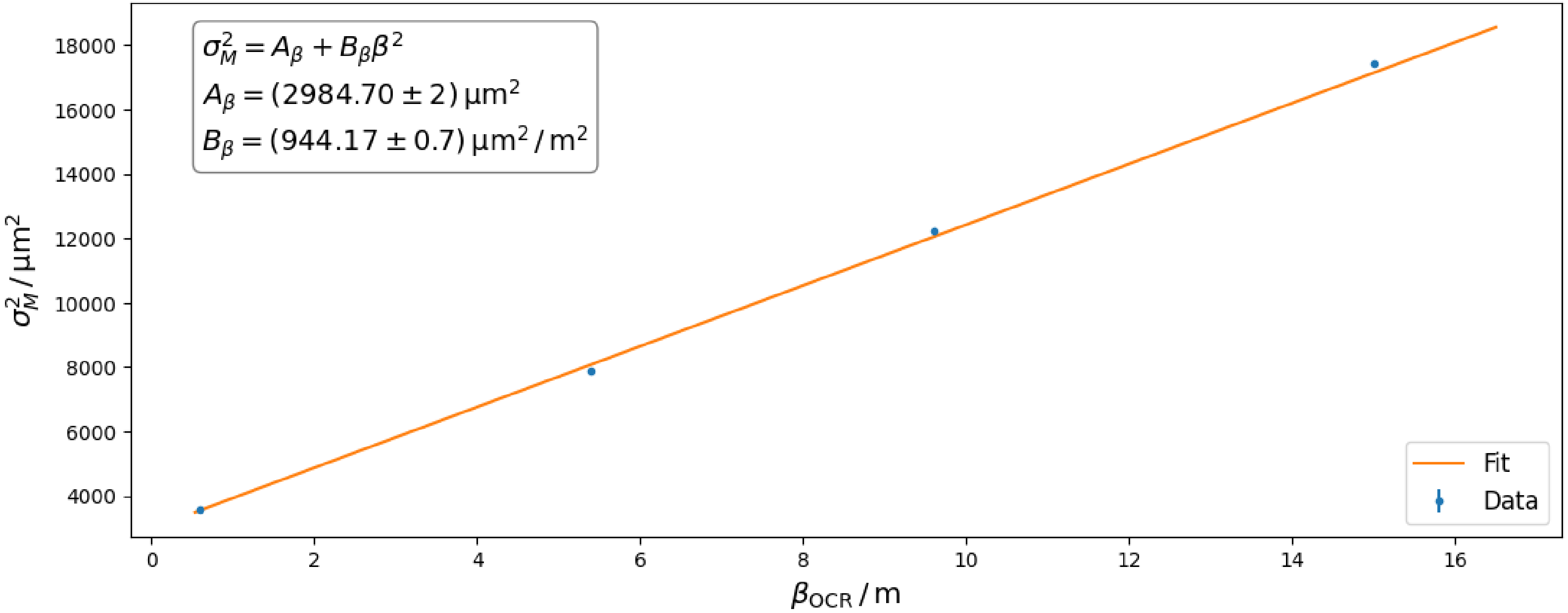




Beta Scan

$$\sigma_M^2 = \sigma_R^2 + \underbrace{\sigma_B^2}_{\text{Vary}} + \underbrace{\frac{D^2}{E^2}\sigma_E^2 + \frac{D^2}{E^2}(ekV)^2\sigma}_{\text{Fix}}$$

$$\sigma_M^2 = A_\beta + \sigma_B^2 = A_\beta + B_\beta\beta_x$$



Consistency of results

$$\sigma_M^2 = \sigma_R^2 + \sigma_B^2 + \frac{D^2}{E^2}\sigma_E^2 + \frac{D^2}{E^2}(ekV)^2\sigma_I^2$$

$$\sigma_M^2 = A_V + B_V V^2$$

$$\sigma_M^2 = A_D + B_D D^2$$

$$\sigma_M^2 = A_\beta + B_\beta \beta_x$$

$$\sigma_E = \frac{E_0}{D_0}\sqrt{A_V - A_D}$$

$$\sigma_I = \frac{E_0}{D_0 ek}\sqrt{B_V}$$

$$\sigma_B = \sqrt{B_\beta \beta_x^0}$$

$$B_\beta = \sigma_I^2(\beta_y^0 + 0.25L^2\gamma_y^0 - L\alpha_y^0)^{-1}$$

$$\sigma_R = \sqrt{A_D - \sigma_B^2}$$

$$\sigma_E = \frac{E_0}{D_0}\sqrt{D_0^2 B_D - V_0^2 B_V}$$

$$\sigma_I = \frac{E_0}{D_0 ekV_0}\sqrt{D_0^2 B_D + A_D - A_V}$$

$$\sigma_B = \sqrt{A_D + B_D D_0^2 - A_\beta}$$

$$B_\beta = \varepsilon_n \gamma_0^{-1}$$

$$\sigma_R = \sqrt{A_\beta - B_D D_0^2}$$

Consistency of Results 2

$$\sigma_M^2 = \sigma_R^2 + \sigma_B^2 + \frac{D^2}{E^2}\sigma_E^2 + \frac{D^2}{E^2}(ekV)^2\sigma_I^2$$

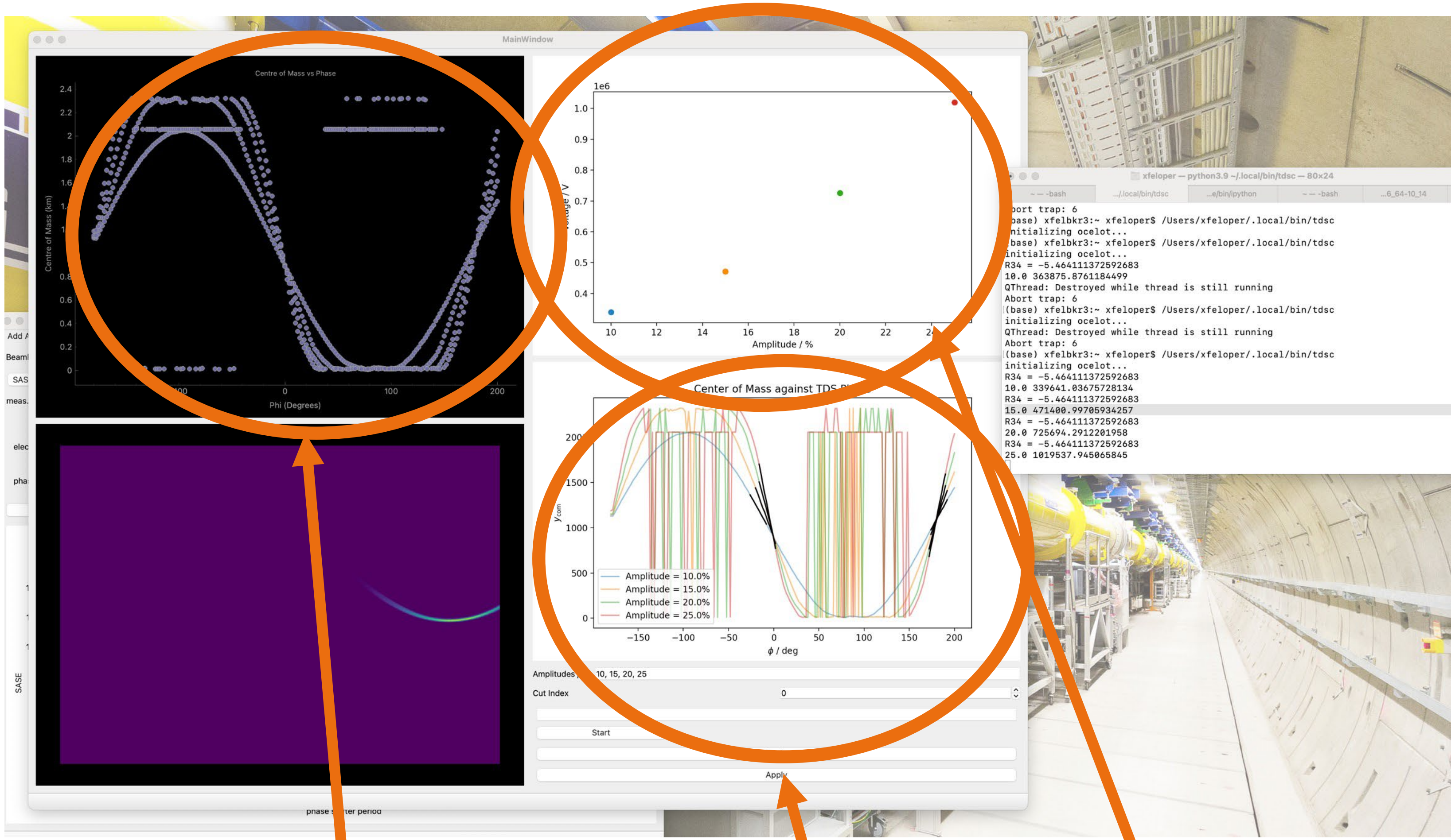
Variable	Value	Alt. Value	Units
V_0	-0.63	-	MV
D_0	1.169	-	m
A_V	$(3.043 \pm 0.002) \times 10^{-9}$	-	m^2
B_V	$(1.326 \pm 0.003) \times 10^{-21}$	-	$\mathrm{m}^2\,\mathrm{V}^{-2}$
A_D	$(1.540 \pm 0.002) \times 10^{-9}$	-	m^2
B_D	$(1.416 \pm 0.002) \times 10^{-9}$	-	
A_β	-	$(2.985 \pm 0.002) \times 10^{-9}$	m^2
B_β	-	$(9.442 \pm 0.007) \times 10^{-10}$	m
σ_E	4.313 ± 0.004	4.187 ± 0.005	keV
σ_I	$(6.444 \pm 0.008) \times 10^{-5}$	$(5.88 \pm 0.03) \times 10^{-5}$	m
σ_B	$(2.834 \pm 0.004) \times 10^{-5}$	$(2.215 \pm 0.009) \times 10^{-5}$	m
σ_R	$(2.714 \pm 0.005) \times 10^{-5}$	$(3.239 \pm 0.005) \times 10^{-5}$	m
ε_x	0.3408 ± 0.0009	0.2403 ± 0.0002	mm · mrad

2022 data with beta scan
(Attempting to recreate 2021)

New Tooling

TDS Calibration

- Additionally the TDS needs to be calibrated for each measurement campaign to get the voltage → also takes up to an hour.
- Also developed an injector TDS calibration GUI
  - Automatically scan TDS “amplitudes” and phases to build mapping of amplitudes [%] to voltages [MV] → Gives all downstream longitudinal calibrations!
  - Also useful for non-invasive emittance and bunch length measurements.
- **Bottom line:** calibrate the injector TDS in a few minutes with no human intervention.



Amplitudes 10, 15, 20, 25

Cut Index 0

```
ort trap: 6
base) xfelbkr3:~ xfeloper$ /Users/xfeloper/.local/bin/tdsc
nitializing ocelot...
base) xfelbkr3:~ xfeloper$ /Users/xfeloper/.local/bin/tdsc
initializing ocelot...
R34 = -5.464111372592683
10.0 363875.8761184499
QThread: Destroyed while thread is still running
Abort trap: 6
(base) xfelbkr3:~ xfeloper$ /Users/xfeloper/.local/bin/tdsc
initializing ocelot...
QThread: Destroyed while thread is still running
Abort trap: 6
(base) xfelbkr3:~ xfeloper$ /Users/xfeloper/.local/bin/tdsc
initializing ocelot...
R34 = -5.464111372592683
10.0 339641.03675728134
R34 = -5.464111372592683
15.0 471400.99705934257
R34 = -5.464111372592683
20.0 725694.2912201958
R34 = -5.464111372592683
25.0 1019537.945065845
```

Image centre of mass vs phase

Amplitude to voltage mapping (the calibration final result).

B2 calibrator development ongoing.
Non-invasive development ongoing.

Extracted zero-crossing gradients at each amplitude