Recent Slice Energy Spread Measurements in the EuXFEL Injector

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Hamburg, 26/09/2023

Overview

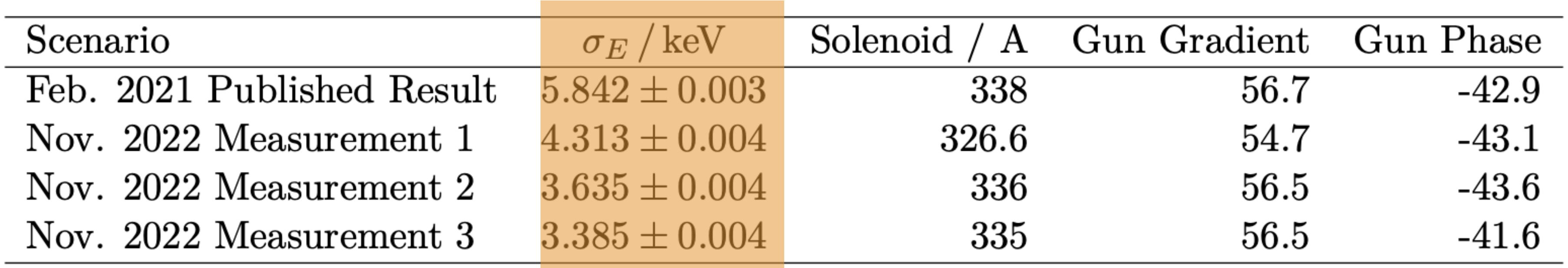
Subheading, optional

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, but actual optimal value unknown.
- Regardless, understanding uncorrelated energy spread is necessary to improve machine reproducibility and understanding.
  - Dynamics not understood, unable to recreate measured slice energy spread 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—**15keV** @ 200pC & >100MeV.
- EuXFEL, 2021: Similar approaching involving a dispersion scan—**6keV** @ 250pC & 130MeV. PITZ 2022 — **2 keV** @ 250pC & 20MeV. 10.1103/PhysRevAccelBeams.25.083401
- SwissFEL, 2022: Contribution of the microbunching instability and intra-beam scattering evidenced by varying the optics -> **reduced** by adjusting optics and disabling LH chicane. 10.1103/PhysRevAccelBeams.25.104401
- EuXFEL, 2022, 2023: Now measured **4keV**, reduced to ~3.4keV with some manipulation of the solenoid current. Unpublished.
  - The energy spread has stayed stable since then, at about ~4keV.



Scenario	σ_E / keV	Solenoid / A	Gun Gradient	Gun Phase
Feb. 2021 Published Result	5.842 ± 0.003	338	56.7	-42.9
Nov. 2022 Measurement 1	4.313 ± 0.004	326.6	54.7	-43.1
Nov. 2022 Measurement 2	3.635 ± 0.004	336	56.5	-43.6
Nov. 2022 Measurement 3	3.385 ± 0.004	335	56.5	-41.6

The Usual Approach

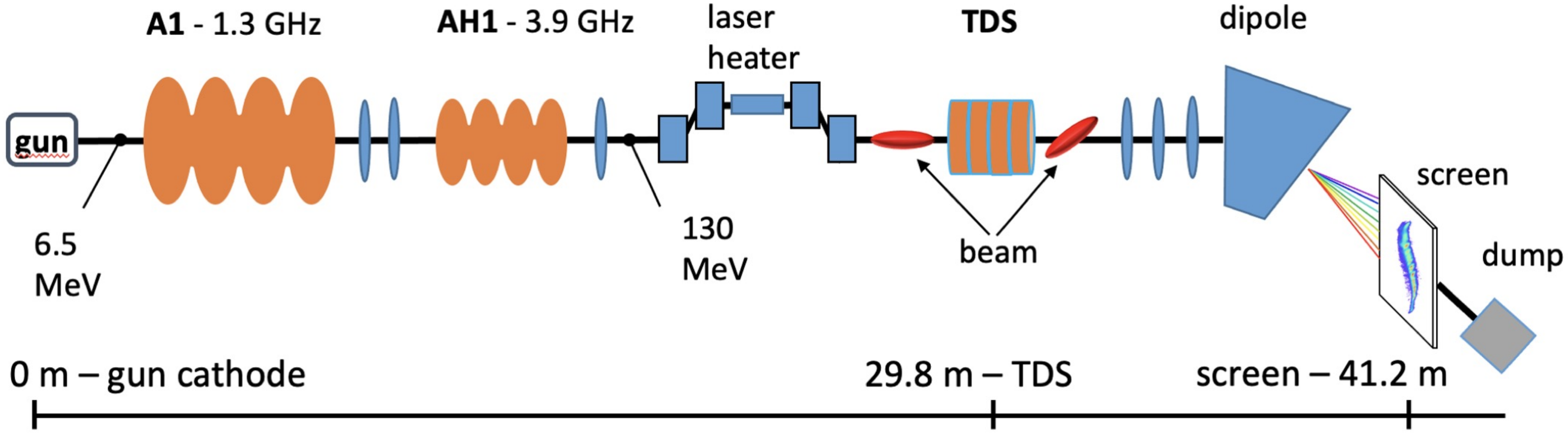
Only provides an upper limit on uncorrelated spread σ_E.

Neglected contributions to size:

- Betatronic
- TDS-induced energy spread
- Imaging resolution

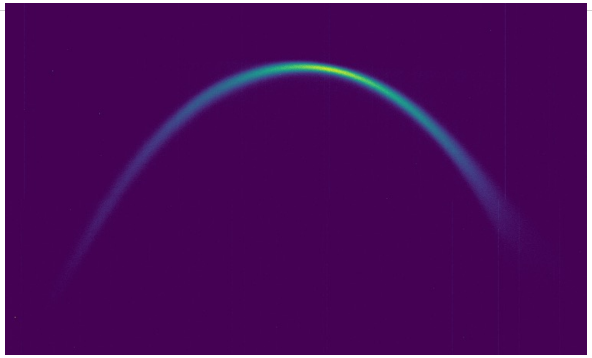
In the injector these contributions can be larger than the slice energy spread's contribution!

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

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

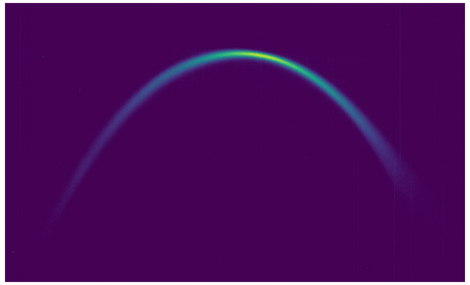
energy spread contribution

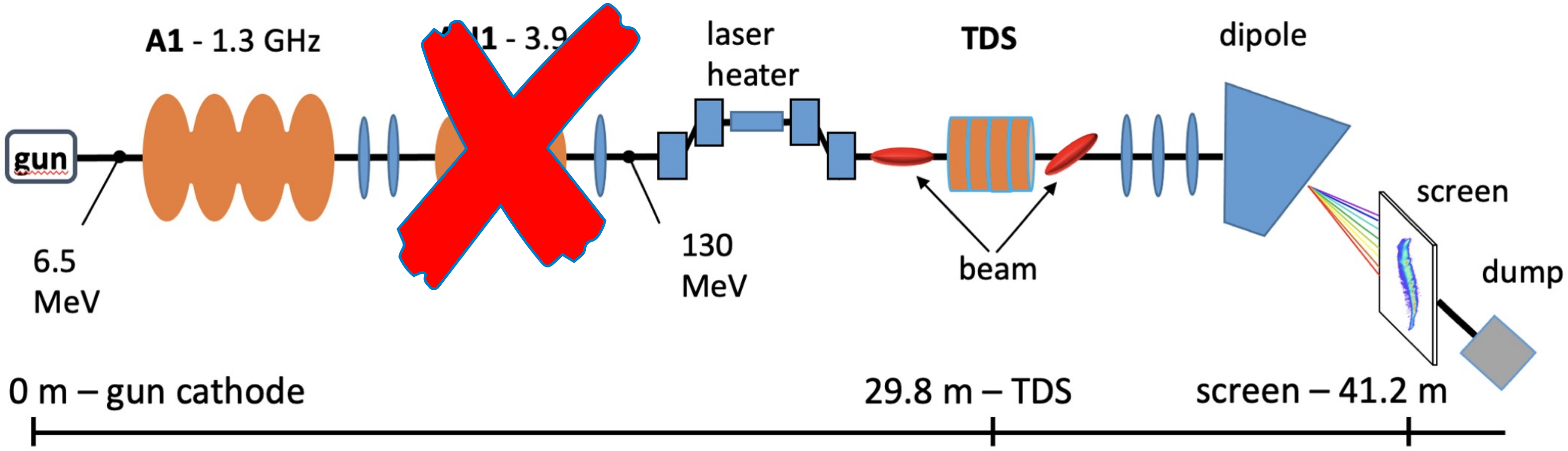
TDS contribution

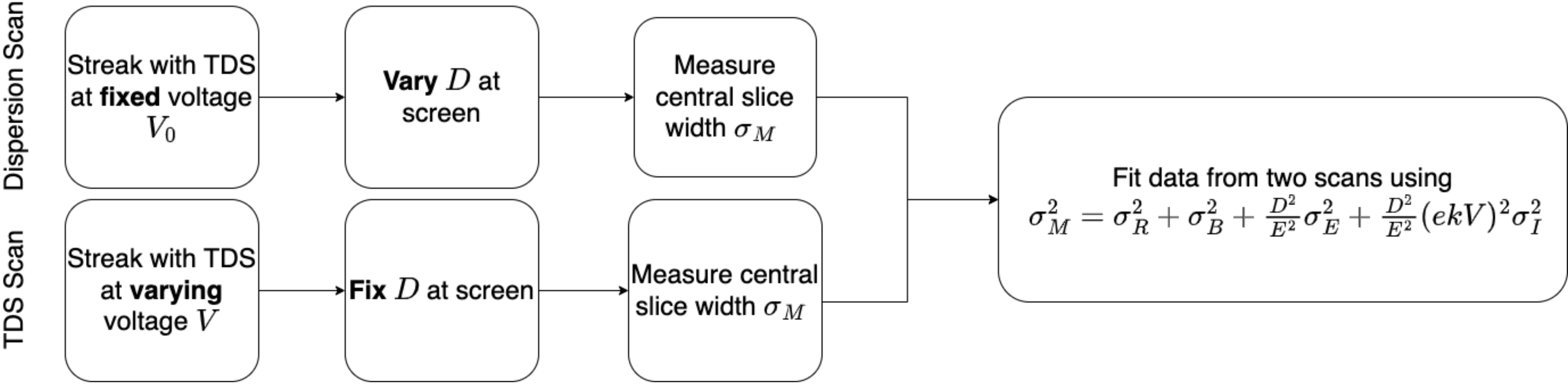
$$\sigma_B^2 = \frac{\beta_x \varepsilon_n}{\gamma_0}$$

$$\sigma_I^2 = \frac{\varepsilon_n}{\gamma_0}(\beta_y^0 + 0.25L^2\gamma_y^0 - L$$

Measurement Technique







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

For the two scans:

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

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

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

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

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

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

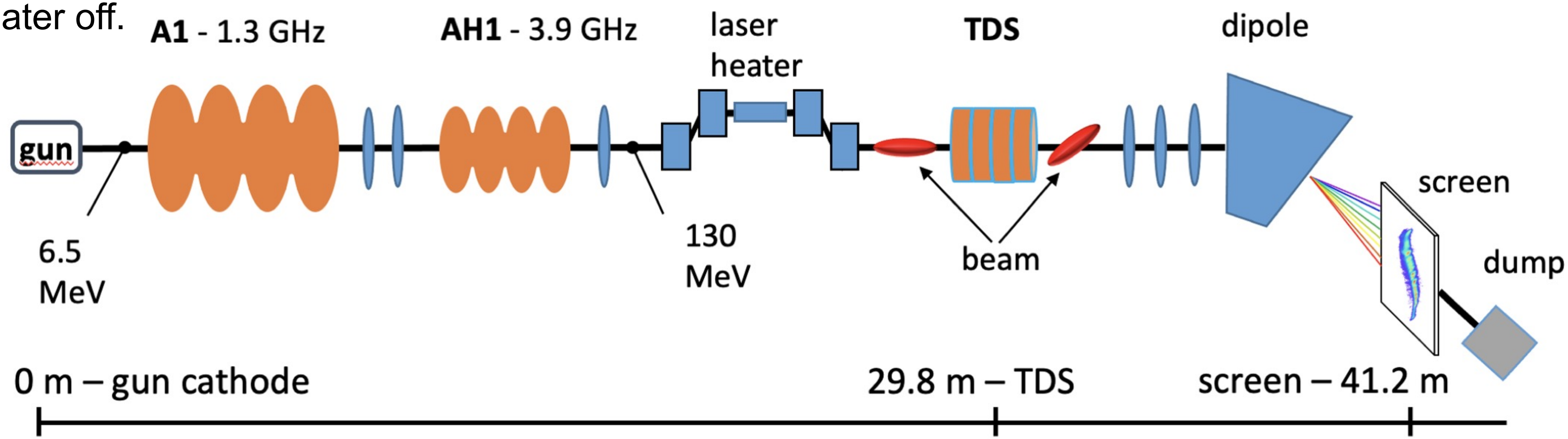
$$B_\beta = \sigma_I^2(\beta_y^0 + 0.25L^2\gamma_y^0 - L\alpha_y^0)^{-}$$

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

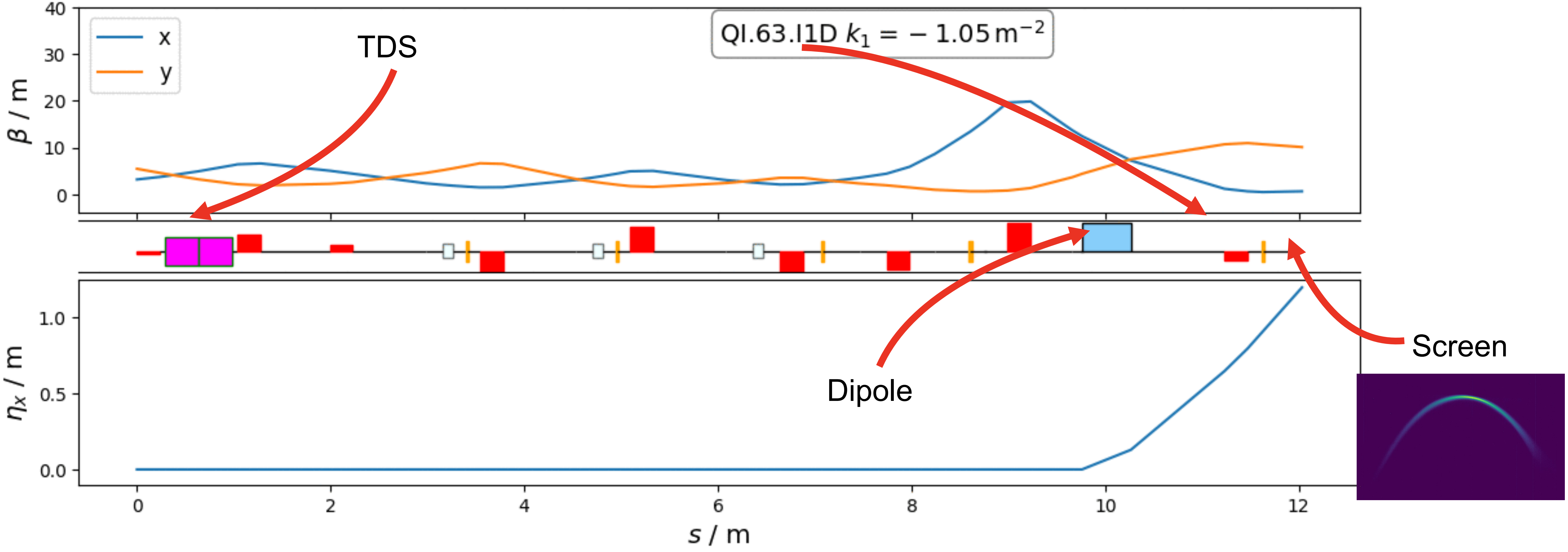
Injector Setup

- 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 using Matthias tool (vital for this measurement)
- Measure the dispersion.



Special optics for measurement from TDS to the screen



TDS

QI.63.I1D $k_1 = -1.05\,\mathrm{m}^{-2}$

Dipole

Screen

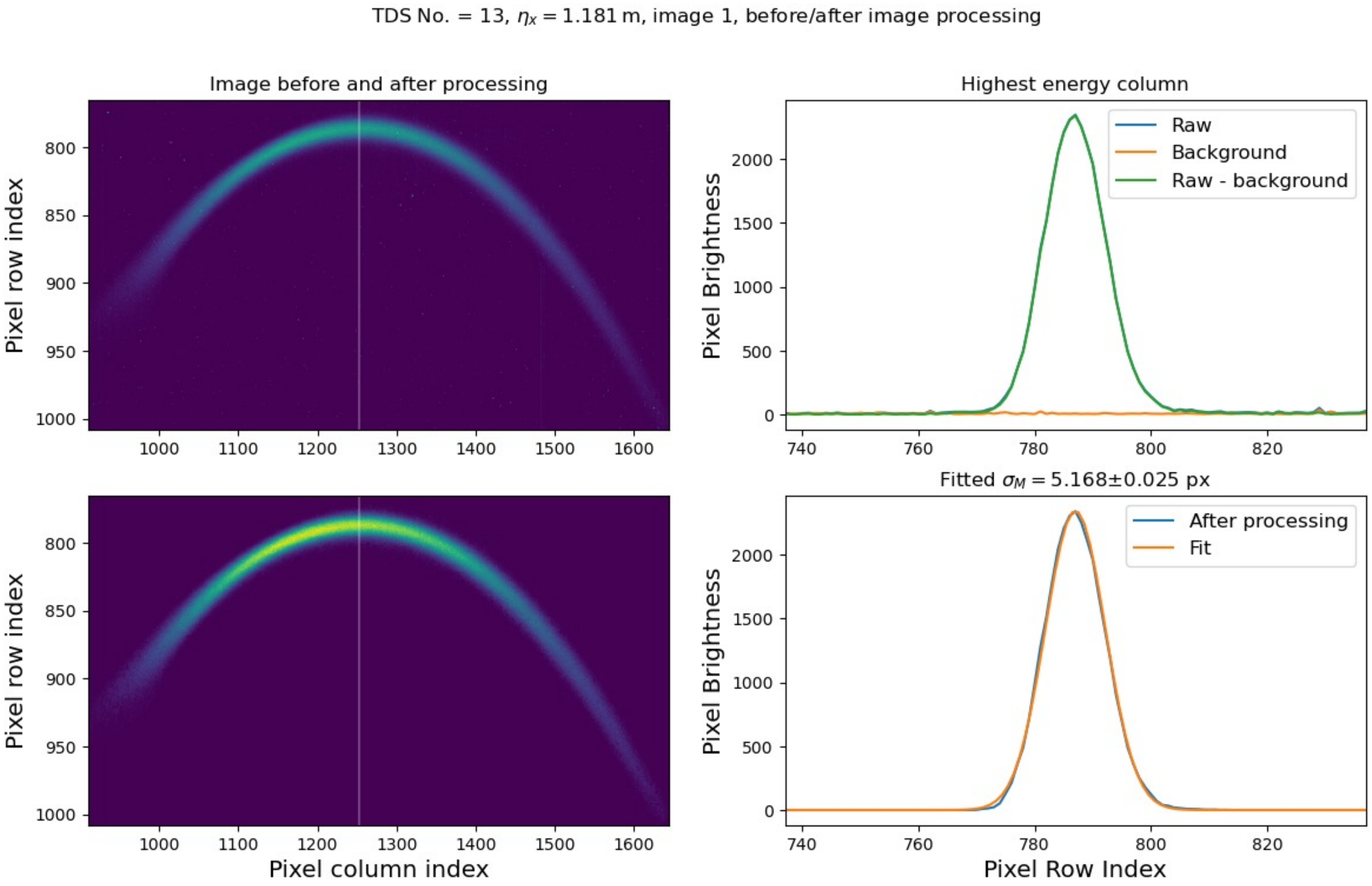
Procedure

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:

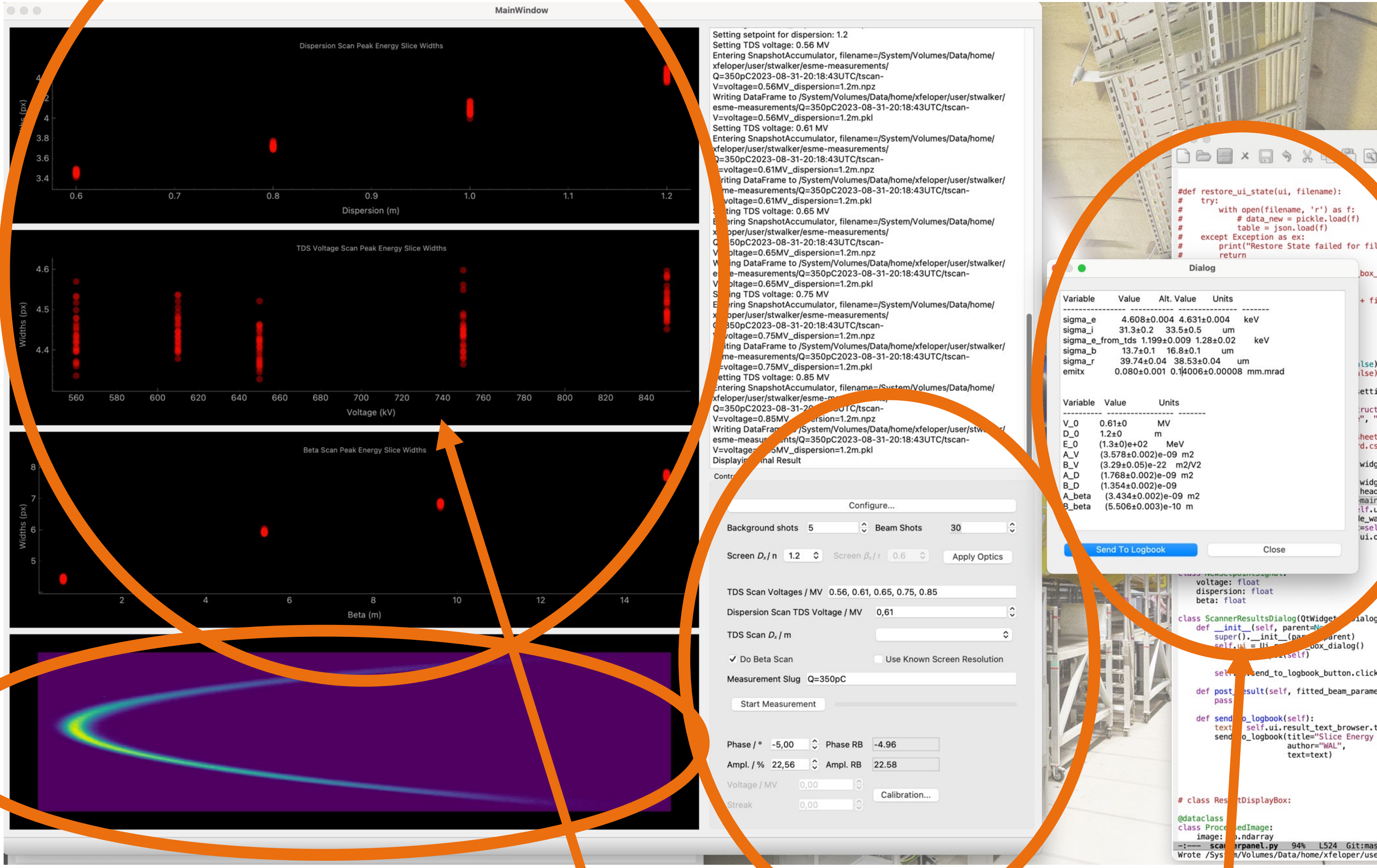
1. Subtract background.
2. Mask to remove isolated blobs.
3. Pick the largest connected non-zero pixel blob to be "the beam".
4. Fit a Gaussian to 10 slices centred on highest energy slice & average.



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.**



```
Setting setpoint for dispersion: 1.2
Setting TDS voltage: 0.56 MV
Entering SnapshotAccumulator, filename=/System/Volumes/Data/home/
xfeloper/user/stwalker/esme-measurements/
Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.56MV_dispersion=1.2m.npz
Writing DataFrame to /System/Volumes/Data/home/xfeloper/user/stwalker/
esme-measurements/Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.56MV_dispersion=1.2m.pkl
Setting TDS voltage: 0.61 MV
Entering SnapshotAccumulator, filename=/System/Volumes/Data/home/
xfeloper/user/stwalker/esme-measurements/
Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.61MV_dispersion=1.2m.npz
Writing DataFrame to /System/Volumes/Data/home/xfeloper/user/stwalker/
esme-measurements/Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.61MV_dispersion=1.2m.pkl
Setting TDS voltage: 0.65 MV
Entering SnapshotAccumulator, filename=/System/Volumes/Data/home/
xfeloper/user/stwalker/esme-measurements/
Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.65MV_dispersion=1.2m.npz
Writing DataFrame to /System/Volumes/Data/home/xfeloper/user/stwalker/
esme-measurements/Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.65MV_dispersion=1.2m.pkl
Setting TDS voltage: 0.75 MV
Entering SnapshotAccumulator, filename=/System/Volumes/Data/home/
xfeloper/user/stwalker/esme-measurements/
Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.75MV_dispersion=1.2m.npz
Writing DataFrame to /System/Volumes/Data/home/xfeloper/user/stwalker/
esme-measurements/Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.75MV_dispersion=1.2m.pkl
Setting TDS voltage: 0.85 MV
Entering SnapshotAccumulator, filename=/System/Volumes/Data/home/
xfeloper/user/stwalker/esme-measurements/
Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.85MV_dispersion=1.2m.npz
Writing DataFrame to /System/Volumes/Data/home/xfeloper/user/stwalker/
esme-measurements/Q=350pC2023-08-31-20:18:43UTC/tscan-
V=voltage=0.85MV_dispersion=1.2m.pkl
Displaying Final Result
```

Configure...

Background shots 5
Beam Shots 30
Screen D_x / n 1.2
Screen β_x / r 0.6
Apply Optics
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=350pC
Start Measurement
Phase / ° -5,00
Phase RB -4.96
Ampl. / % 22,56
Ampl. RB 22.58
Voltage / MV 0,00
Streak 0,00
Calibration...

```
Variable        Value       Alt. Value     Units
---------------- ----------- --------------- -------
sigma_e          4.608±0.004  4.631±0.004    keV
sigma_i          31.3±0.2    33.5±0.5       um
sigma_e_from_tds 1.199±0.009  1.28±0.02      keV
sigma_b          13.7±0.1    16.8±0.1       um
sigma_r          39.74±0.04   38.53±0.04     um
emitx          0.080±0.001  0.14006±0.00008  mm.mrad


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       (3.578±0.002)e-09  m2
B_V       (3.29±0.05)e-22   m2/V2
A_D       (1.768±0.002)e-09  m2
B_D       (1.354±0.002)e-09
A_beta     (3.434±0.002)e-09  m2
B_beta     (5.506±0.003)e-10  m
```

```
#def restore_ui_state(ui, filename):
#    try:
#        with open(filename, 'r') as f:
#            # data_new = pickle.load(f)
#            table = json.load(f)
#    except Exception as ex:
#        print("Restore State failed for fil
#        return
```

```
    voltage: float
    dispersion: float
    beta: float

class ScannerResultsDialog(QtWidget
    def __init__(self, parent=No
        super().__init__(pa    arent)
        self.ui = Ui_      box_dialog()
                       (self)

        sel    send_to_logbook_button.click

    def post_result(self, fitted_beam_parame
        pass

    def send_to_logbook(self):
        text = self.ui.result_text_browser.t
        send_to_logbook(title="Slice Energy
                        author="WAL",
                        text=text)



# class ResultDisplayBox:

@dataclass
class ProcessedImage:
    image: np.ndarray
-:---  scannerpanel.py   94%   L524  Git:mas
Wrote /System/Volumes/Data/home/xfeloper/use
```

Post-processed image

Slice widths

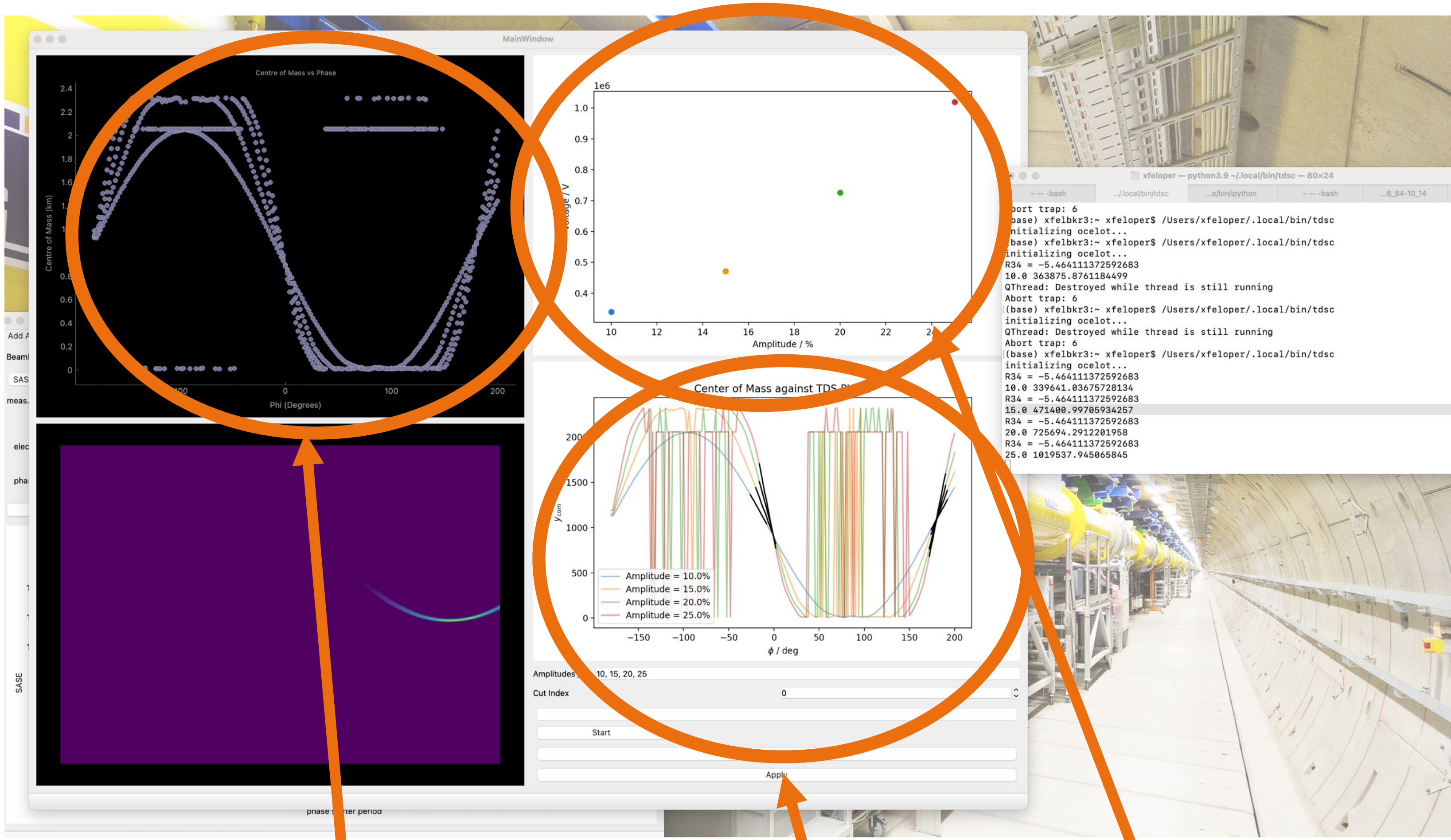
Measurement control

Measurement result

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

```
bort 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
```

Amplitude to voltage mapping (the calibration final result).

Image centre of mass vs phase

Extracted zero-crossing gradients at each amplitude

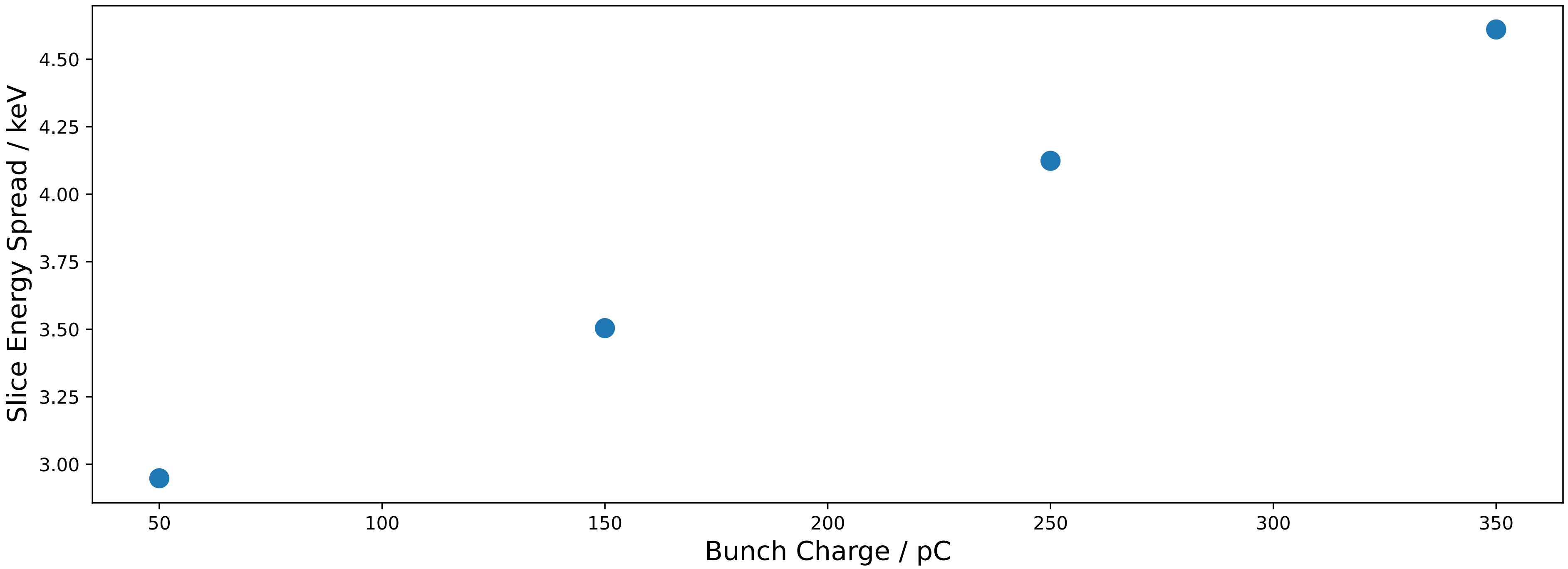
B2 calibrator development ongoing.
Non-invasive development ongoing.

Experiment details

- We did two scans over a single four hour shift.
    - Charge scan: 50pC, 150pC, 250pC and 350pC
    - R_{56} scan: -1mm, -2.5mm, -4.336mm (nominal), -5.5mm and -7mm.
- 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).
- We used the new online data data taking and analysis software for these scans, as well as for calibrating the TDS.

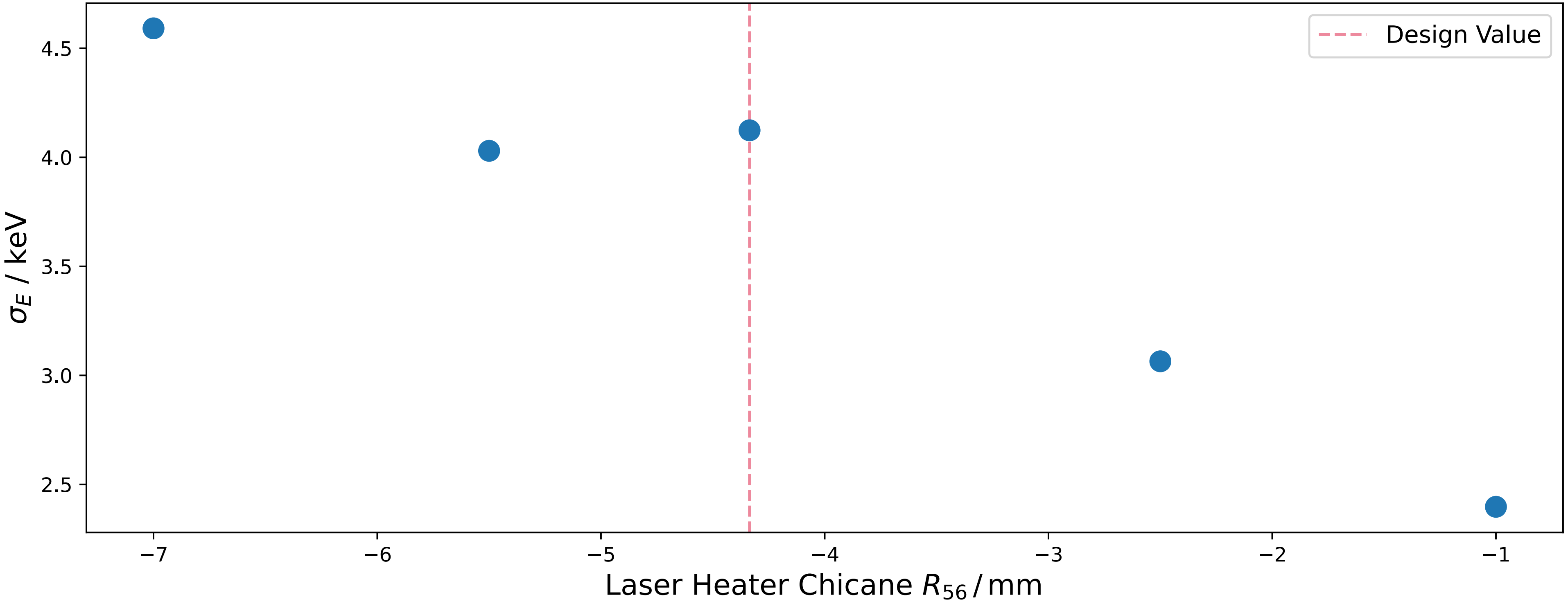
Charge Scan

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



R_{56} Scan

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

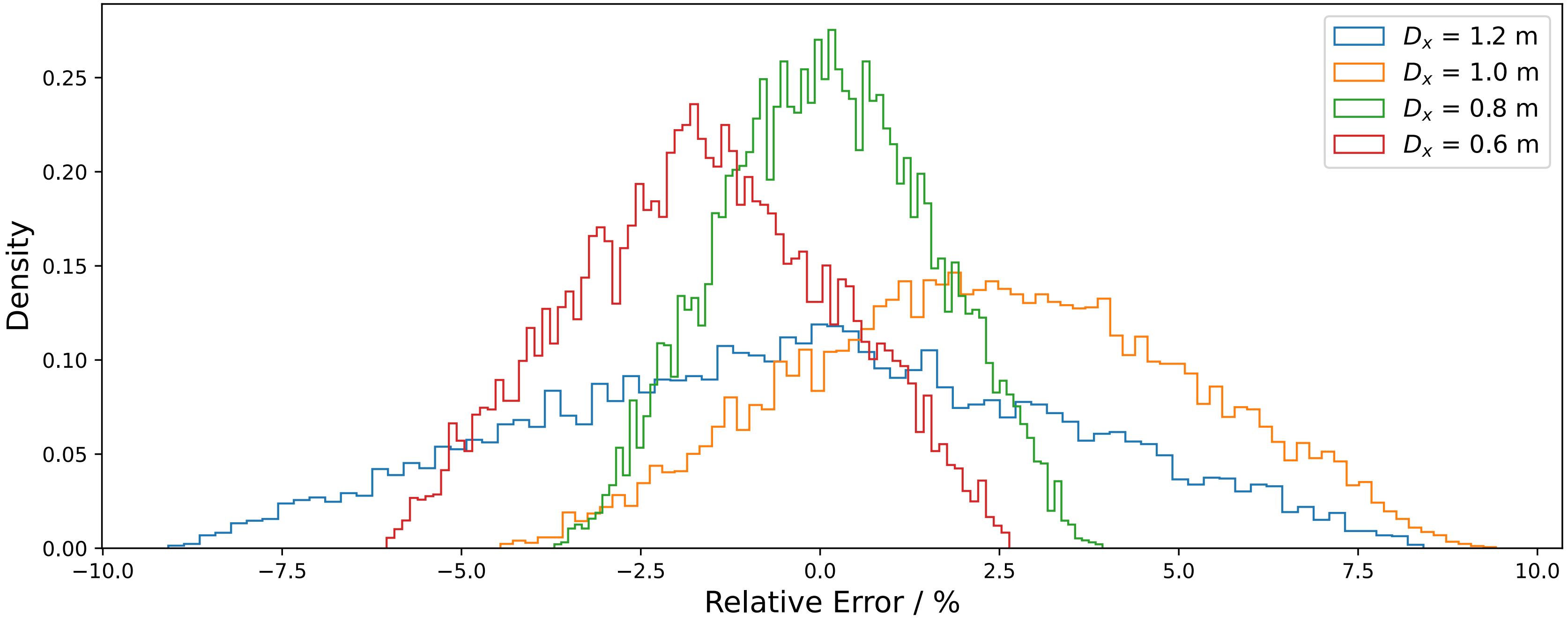


Measurement Details

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”.

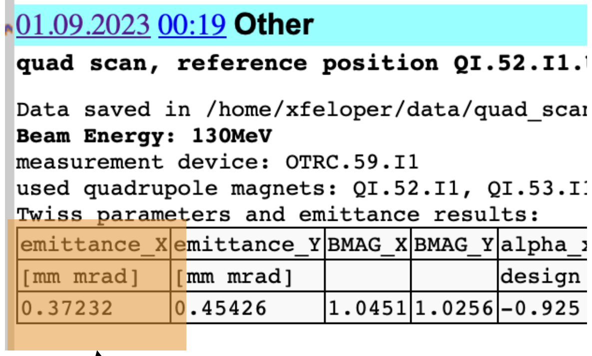
- Simulated in OCELOT.
- Dispersion at the screen is tolerant to even large changes in the LH dipoles.
- Nevertheless should measure the dispersion in future experiments.
- Translates max ±10% error in energy spread.



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?



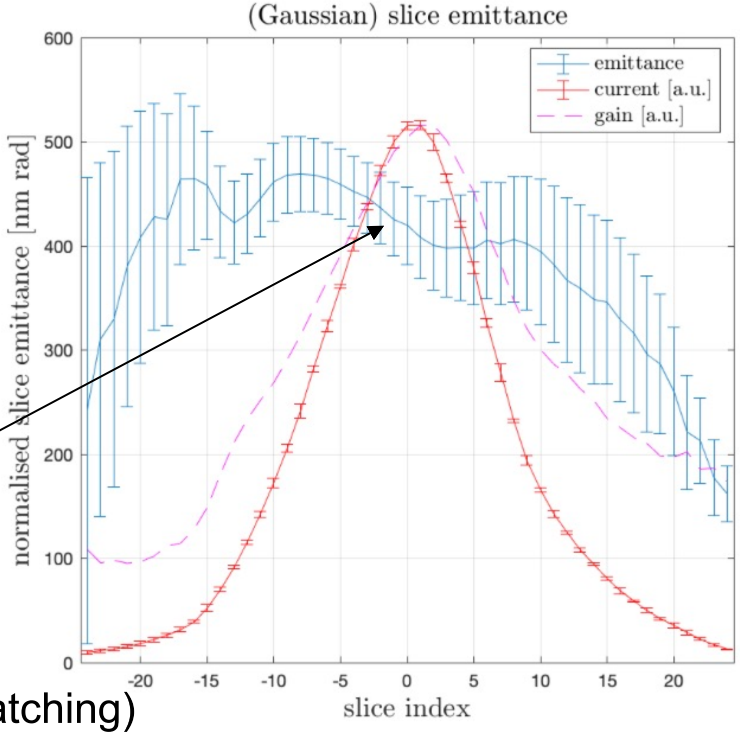
01.09.2023 00:19 **Other**

quad scan, reference position QI.52.I1.

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

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

ref



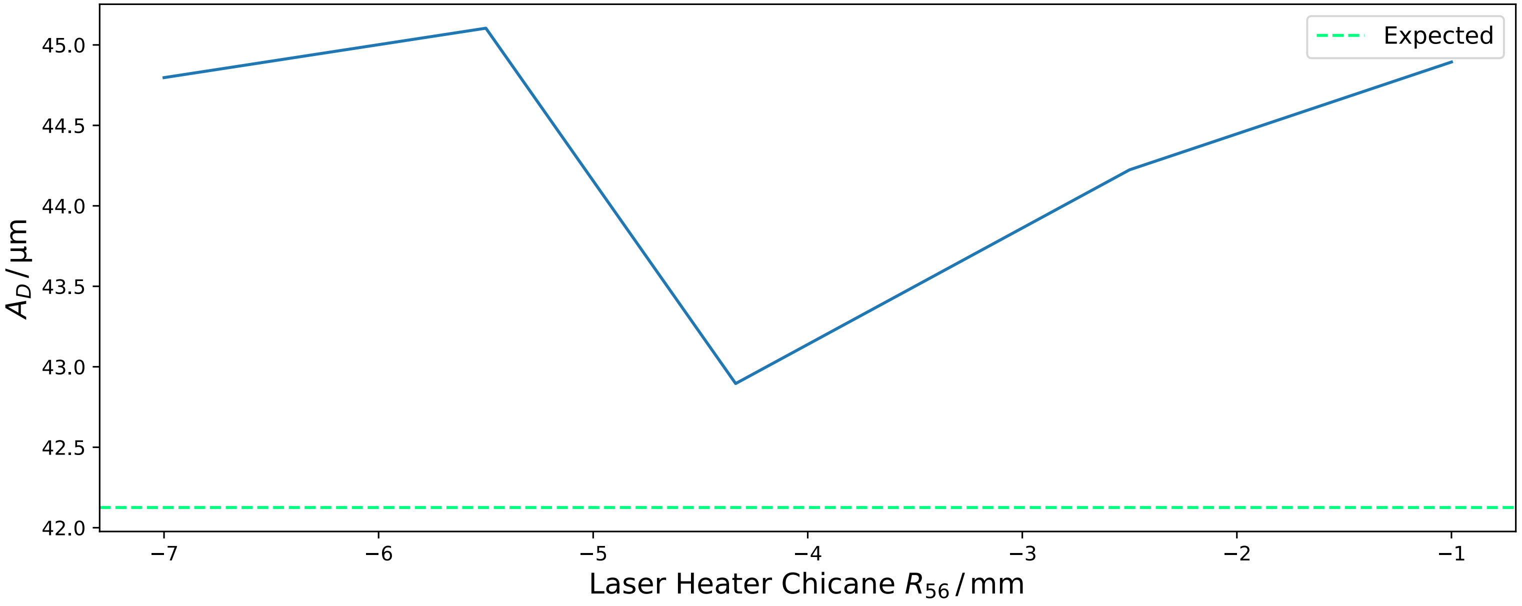
Projected

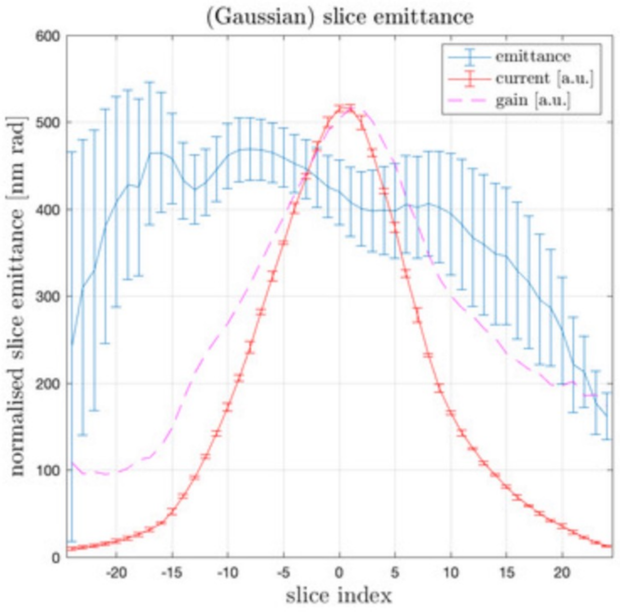
Central slice (0.45 mm•mrad)
measured a minute later (no matching)

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).





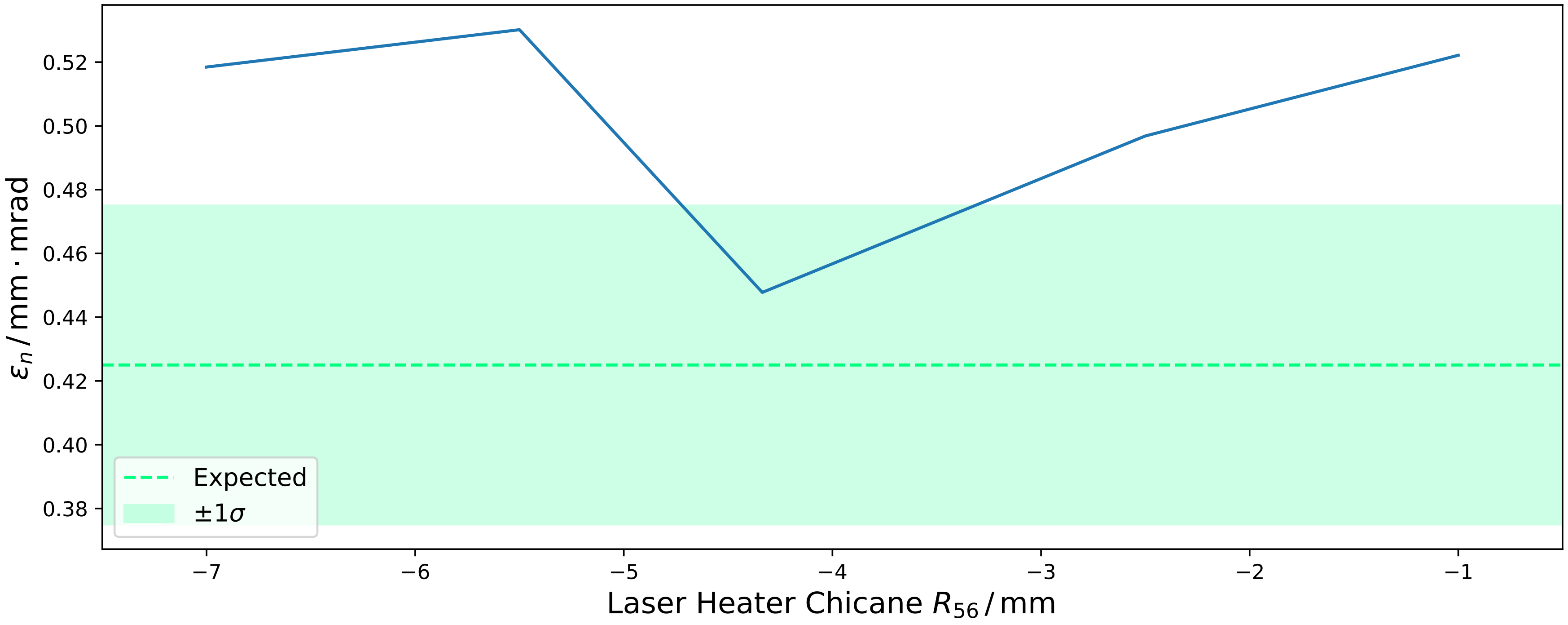
The Matthias Tool

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?



Conclusion

- The slice energy spread shows wide tunability based on the charge and laser heater chicane R_{56}.
  - (2.4–4.5) keV from -1mm to -7mm R_{56} @ 250pC
  - (3.0–4.5) keV from 50pC to 350pC @ nominal $R_{56.}$
- In combination with the longer term decrease from ~6keV to 4keV in the last two years for unknown reasons, it is clear that there is still a lot to be understood about the LPS 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 fast results. Room for further studies of other parameters, e.g. bunch length.

Outlook

- Upcoming blue week in October for additional chicane studies.
- Aiming to take part in the upcoming Nepal laser commissioning—-bunch length scans (not possible with laser 2).
- We would still like to provide an absolute calibration of the laser heater.
- IBS simulation work ongoing with Erion to ground these results more in theory.
- Further work on the GUI and tooling to improve usability and speed.
- Broader GUI development will feed back into parasitic bunch length and slice emittance measurements for use in normal operation.

Final Slide

- Thanks also to:
    - Frank (beam energy coming out of the gun measurement)
    - Torsten (useful and interesting conversations regarding laser heater)
    - Weilun (night shift moral support)
- Questions?

Thank you

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