Slice Energy Spread Measurements in the EuXFEL Injector

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HELMHOLTZ

DESY.

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 in 2024 in the **EuXFEL injector**.

Our Results at Rome LEDS

- Slice energy spread changed between 2021 and 2022 (5.8keV → 4.3 keV).
- Strong dependence of the solenoid and gun gradient on the SES.

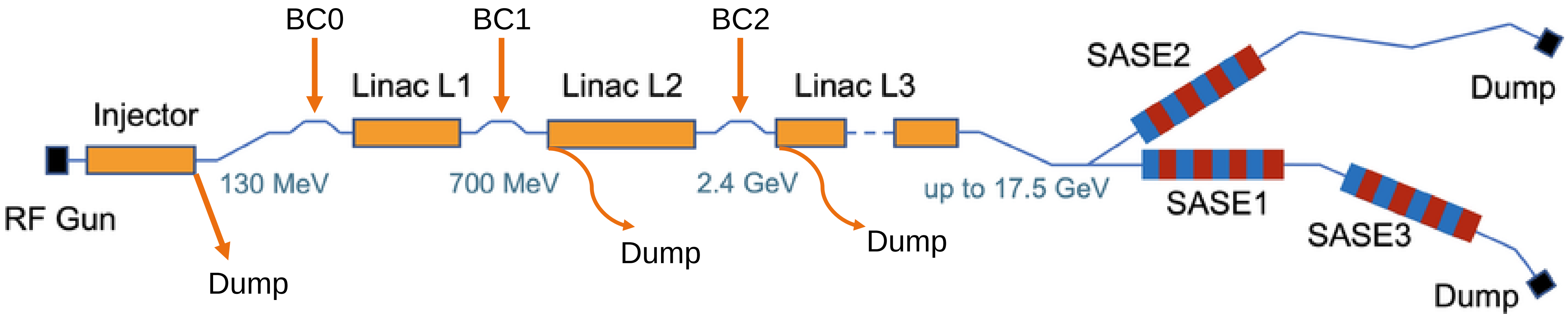
Scenario	σ_E / keV	Solenoid / A	Gun Gradient / MV m^{-1}	Gun Phase / °
Feb. 2021 Published Result	5.842	338	56.7	-42.9
Nov. 2022 Measurement 1	4.313	326.6	54.7	-43.1
Nov. 2022 Measurement 2	3.635	336	56.5	-43.6
Nov. 2022 Measurement 3	3.385	335	56.5	-41.6

- Scans:
  - Strong bunch charge dependence on slice energy spread, from 50pC (3 keV) to 350pC (4.5 keV).
  - Strong LH chicane R_{56} dependence on the energy spread, from -1 mm (2keV) to -7mm (4.5keV).

The EuXFEL

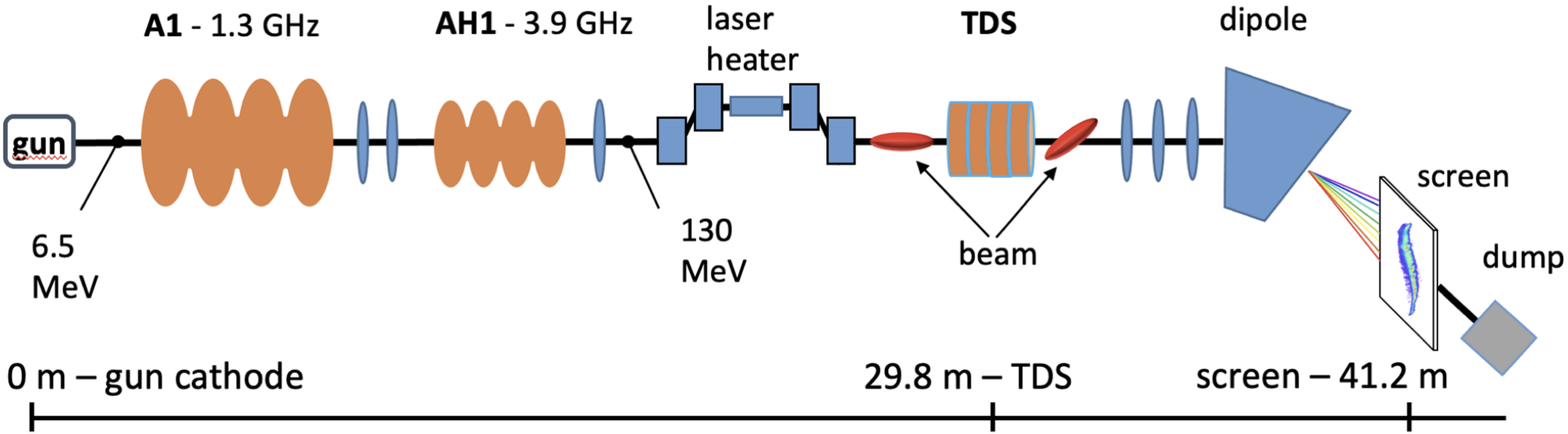
Overview

- 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.



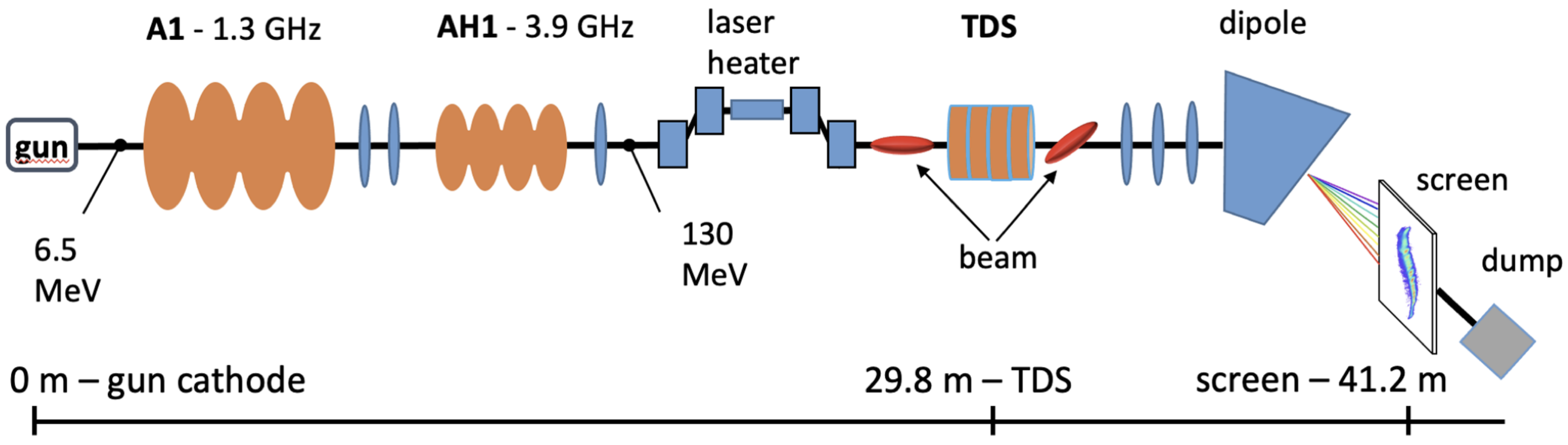
The EuXFEL

Injector



The Usual Approach

Energy Spread Measurement



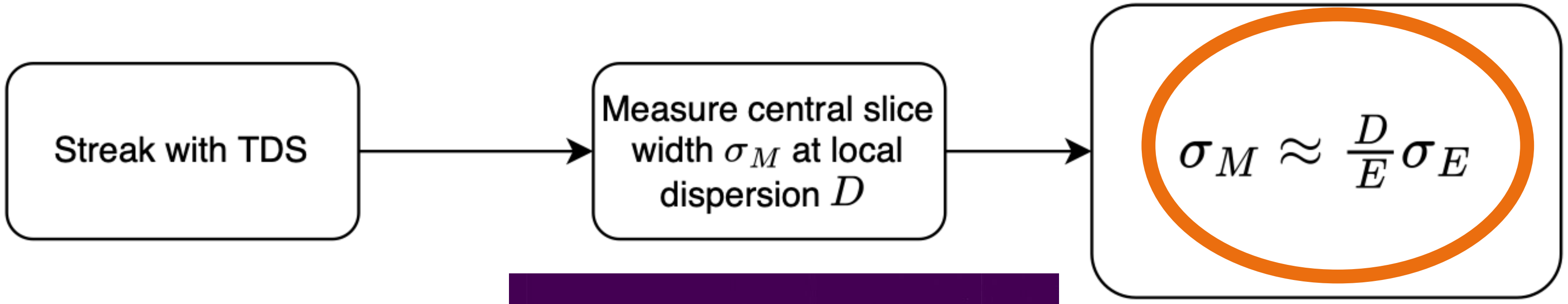
Only provides an upper limit on uncorrelated spread σ_E.

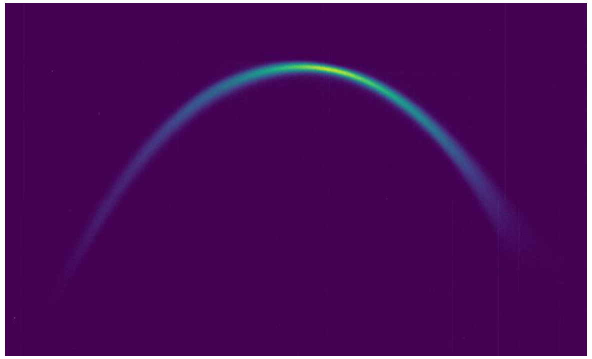
Neglected contributions to size:

- 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...





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

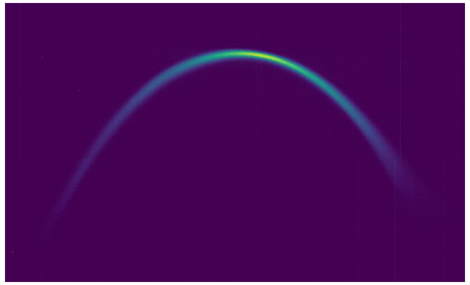
energy spread contribution

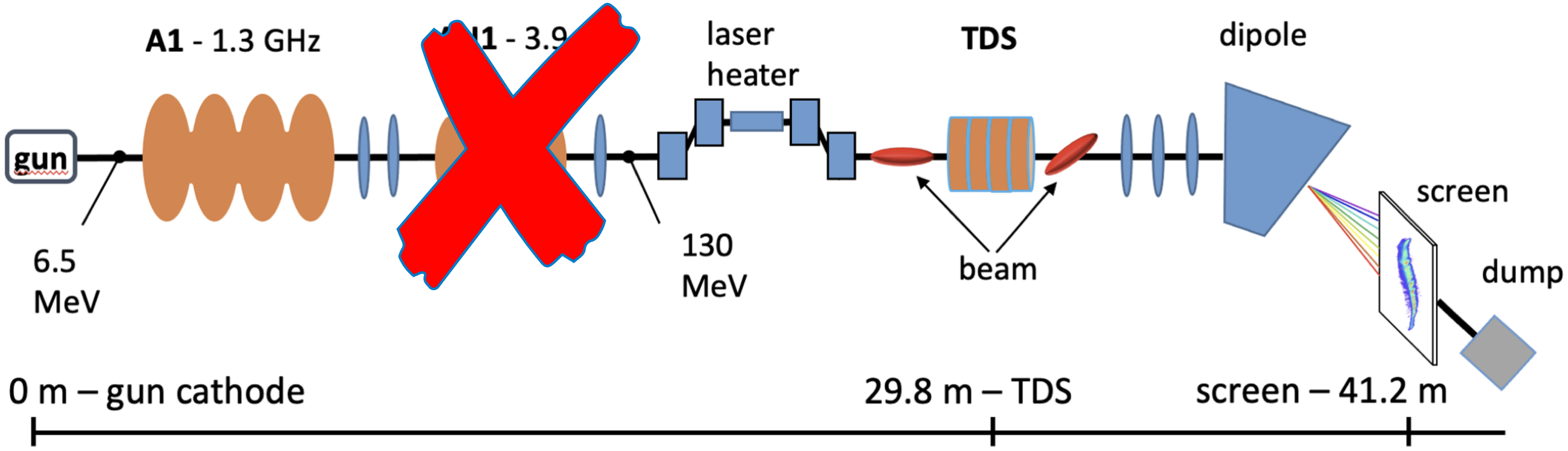
TDS contribution

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

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:

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

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

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

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

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

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

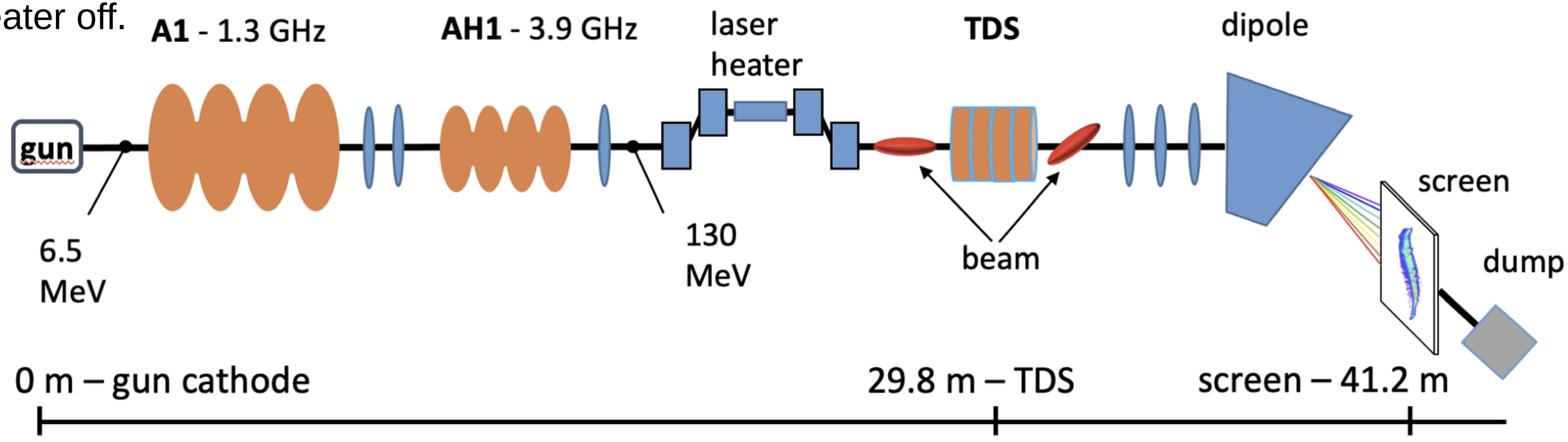
$$\sigma_B = \sqrt{B_\beta \beta_x^0}$$

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

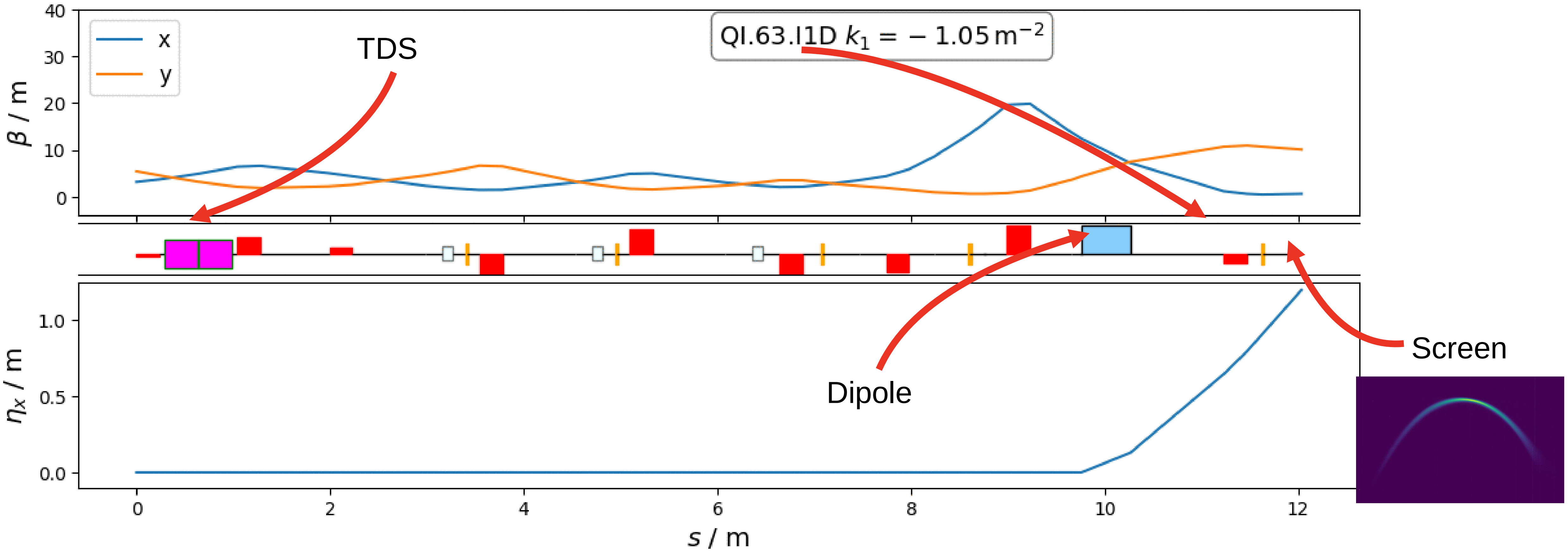
$$\sigma_R = \sqrt{A_D - \sigma_B^2}$$

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



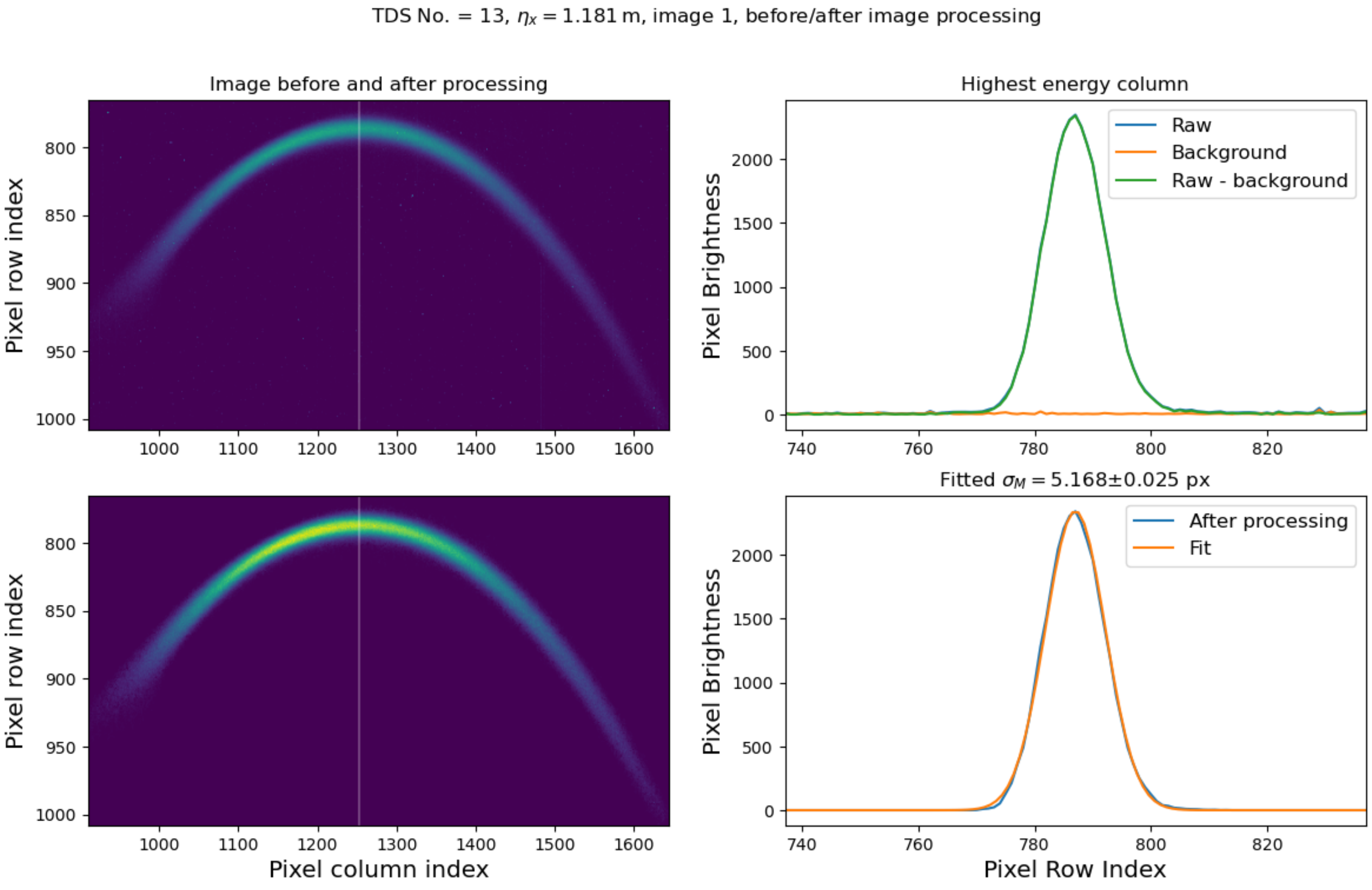
Procedure

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.

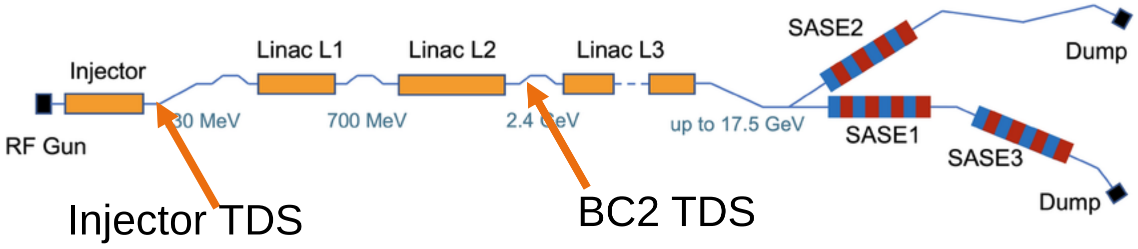
Then:

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.



The State of the TDSs at the EuXFEL

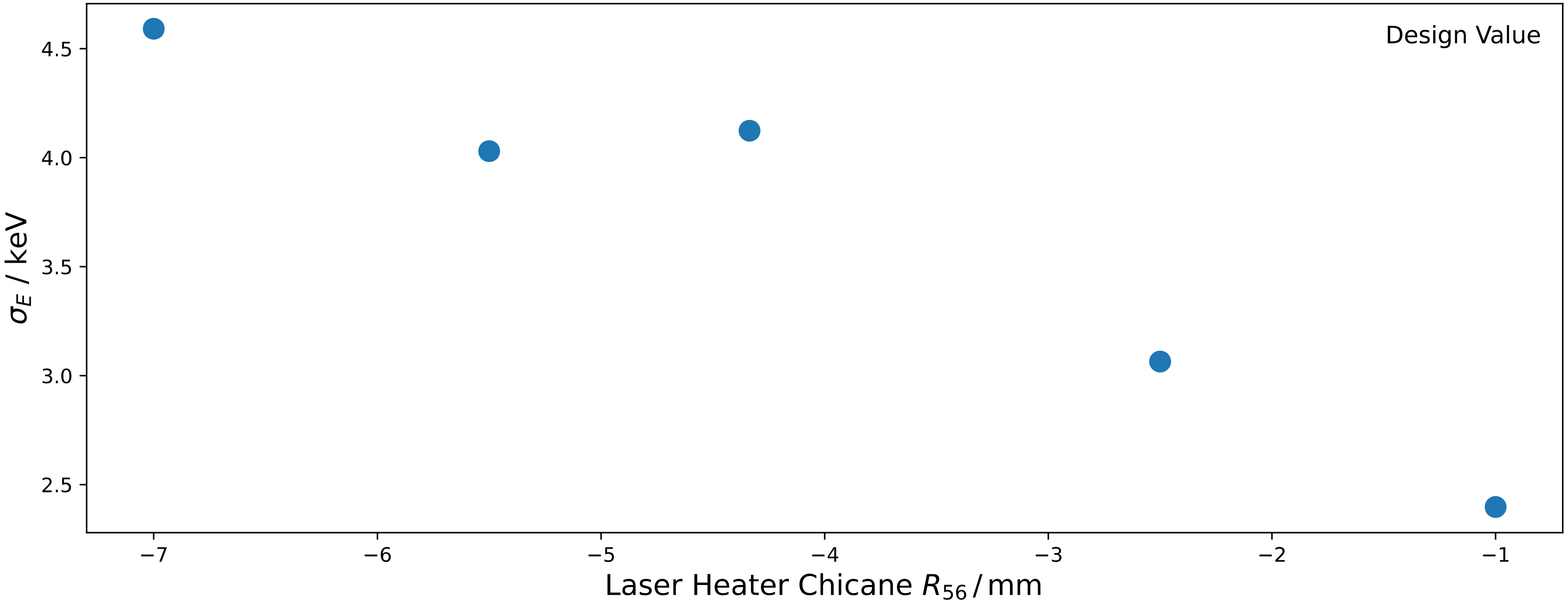
- Injector TDS
  - Modulator caught on fire earlier in the year. Required borrowing modulator from REGAE to bring TDS back online in August.
  - Modulator will be returned to REGAE most likely sometime in October.
  - Going forwards turn around time to bring TDS back online using REGAE modulator ~2 weeks.
- BC2 TDS (post full compression)
  - After attempted pulse compressor upgrade in Winter 2023 to boost time resolution by up to factor 2.
  - Since then, the BC2 TDS has not worked.
  - Recently diagnosed as a timing problem in one of the components.
  - Most likely operating again in 2025.



Laser Heater Chicane R_{56} Scan

Slice Energy Spread

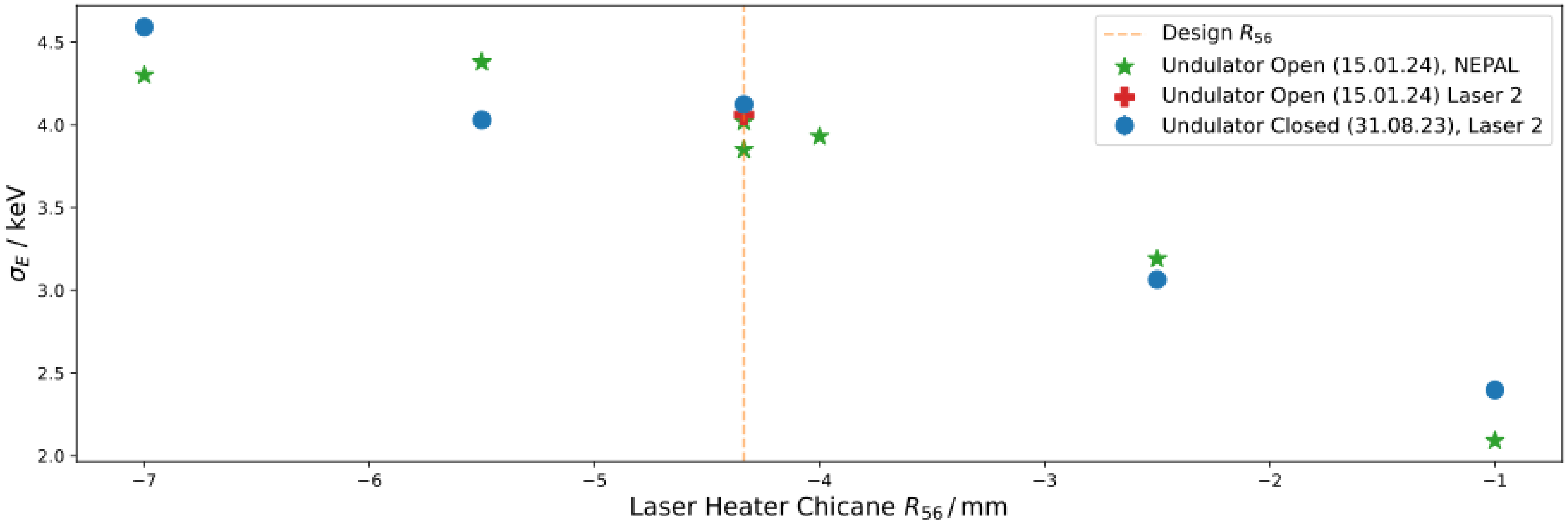
- We previously scanned the R_{56} of the laser heater chicane from -7 mm to -1 mm (the minimum) @ Q = 250 pC.
- Design setting (-4.336 mm) not scanned in order with the other setpoints.
- Strong dependence on LH R_{56} is apparent, from 4.5 keV at maximum to 2.4 keV at minimum.
- Undulator closed (as by design).



Laser Heater Chicane R_{56} Scan

Slice Energy Spread

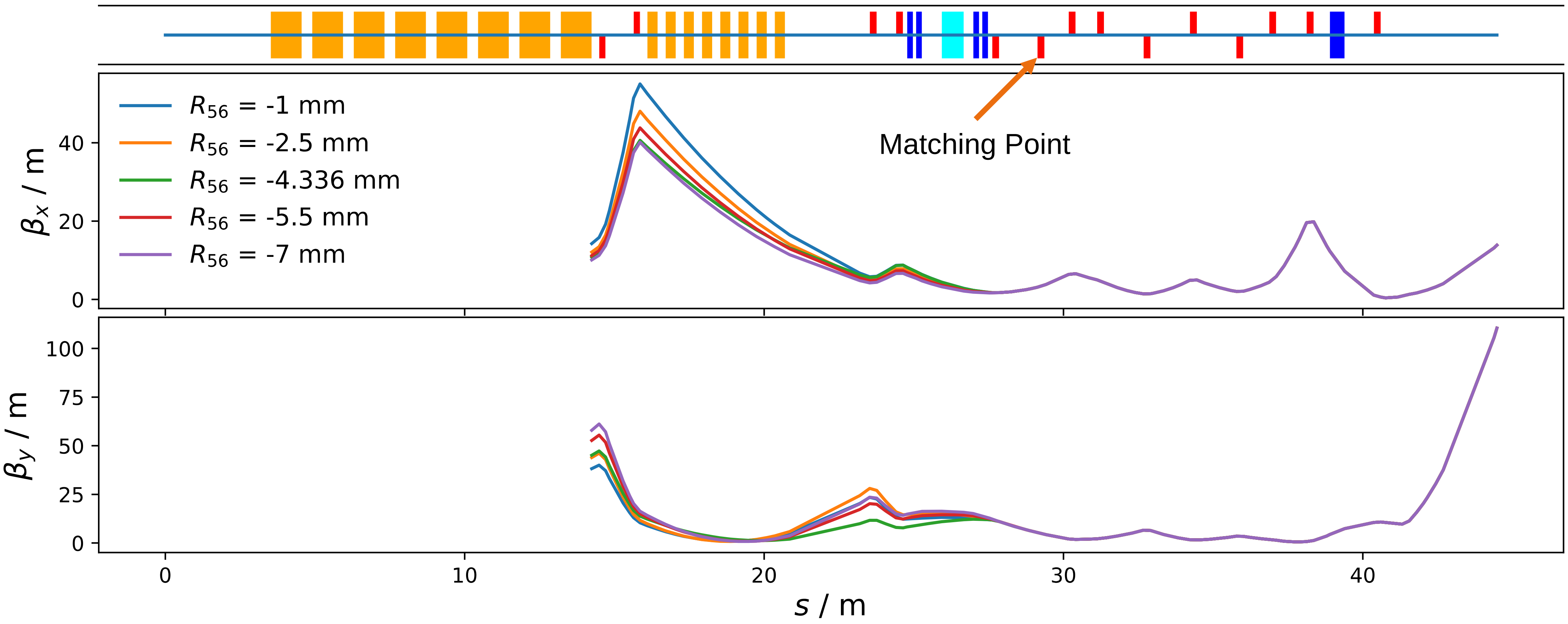
- Repeated the scan with the new laser and with the undulator open:
  - Remove any edge focusing from the undulator → simpler experimental setup.
- Weak dependence on the undulator shown: small differences can be explained as due to undulator edge focusing → different optics → IBS.
- Laser choice impact negligible.



Laser Heater Chicane R_{56} Scan

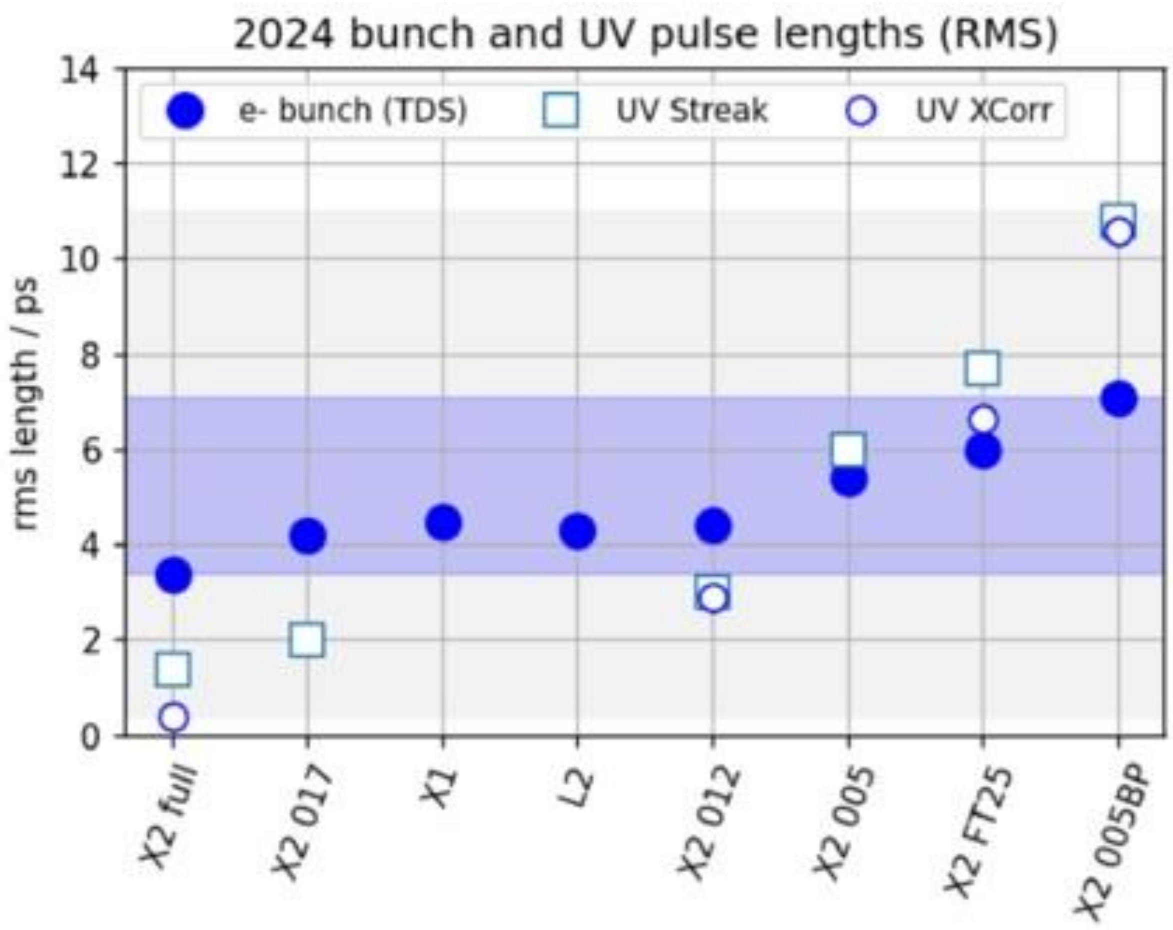
Transverse Optics

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



Energy Spread and Charge Density

- With the new NEPAL laser we can vary the charge density:
  - Keep bunch charge constant and vary the laser pulse length.
- Right: various laser setpoints with RMS laser and resulting RMS bunch lengths from commissioning in July
- Laser pulse lengths from 2ps to 25ps possible with constant charge.
- Intended experiment: vary bunch lengtha nd measure energy spread
  - Pushed back due to TDS maintenance and laser commissioning.
  - Beam time for this experiment set set for October.



Courtesy of YE CHEN

Conclusion

- We continue to investigate the physics of slice energy spread in the EuXFEL injector and linac.
- We repeated our LH R_{56} scan measurement, replicating the strong dependence of the energy spread on the R_{56} independent of undulator setting and laser choice.
  - Needs to yet be understood. Typically one would imagine a multi-stage compression scheme to cause MBI.
  - However, we have only one, relatively weak, chicane in our measurement configuration.
  - Possible microbunching coming out of the gun?
- Our longitudinal diagnostics in the linac have had a tough year
  - The injector TDS is now dependent on swapping in a modulator from a different accelerator as required.
  - BC2 TDS has been offline all year, but forecasted to be available again from January 2025.
- Measurements planned for October:
  - Charge density scan (varying bunch length with constant charge).
  - Laser Heater absolute calibration.
  - Injector slice energy spread versus microbunching and energy spread in SA2.M

Thank you
Vielen Dank

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Backup