Energy Spread Measurements in the EuXFEL Injector

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DESY

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Outline

- ➡ Motivation
- ➡ History
- ➡ Method
- ➡ New Analysis tool and validation on old published data
- ➡ New measurements with results
- ➡ Details
- ➡ Conclusion

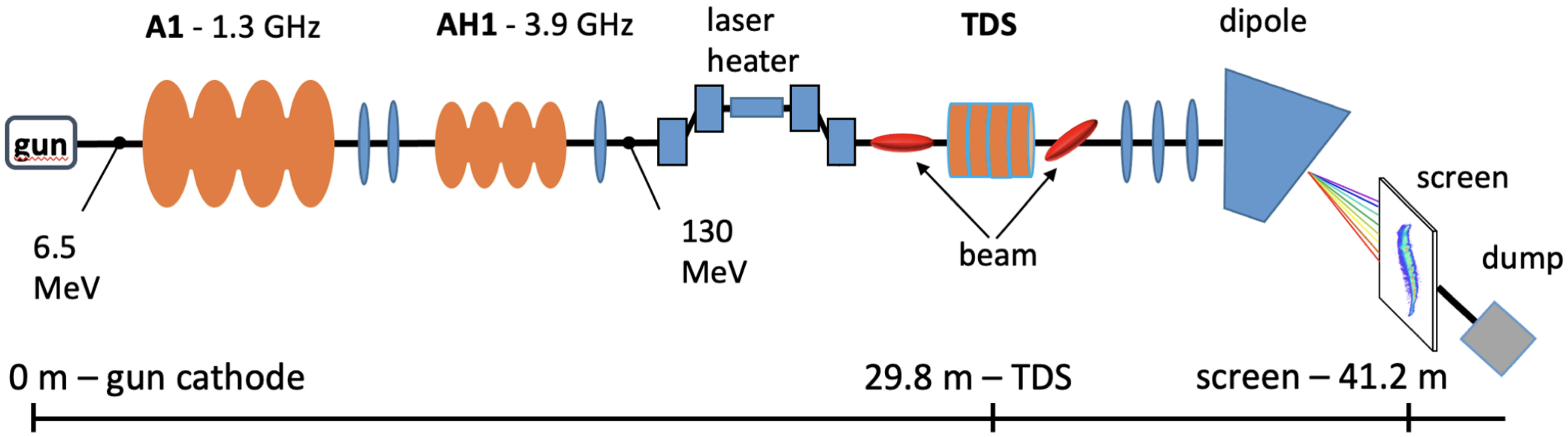
Motivation

- ➡ 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. Typically increased to 8keV with the LH int he euXFEL.
- ➡ 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 simulations.

Context

- 2020: Intrabeam scattering measured at Fermi, but result highly dependent on initial energy spread, which was treated as a free parameter.
  - 2020 New J. Phys. 22 083053
- 2020: SwissFEL— energy spread measurement in the injector using an energy scan—**15keV** @ 200pC & >100MeV .
  - 10.1103/PhysRevAccelBeams.23.090701
- EuXFEL 2021 — Similar approaching involving a dispersion scan—**6keV** @ 250pC & 130MeV.
  - 10.1103/PhysRevAccelBeams.24.064201
- 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.
  - 10.1103/PhysRevAccelBeams.25.104401
- This talk: recent measurements and new results from November 2022.

The Usual Approach



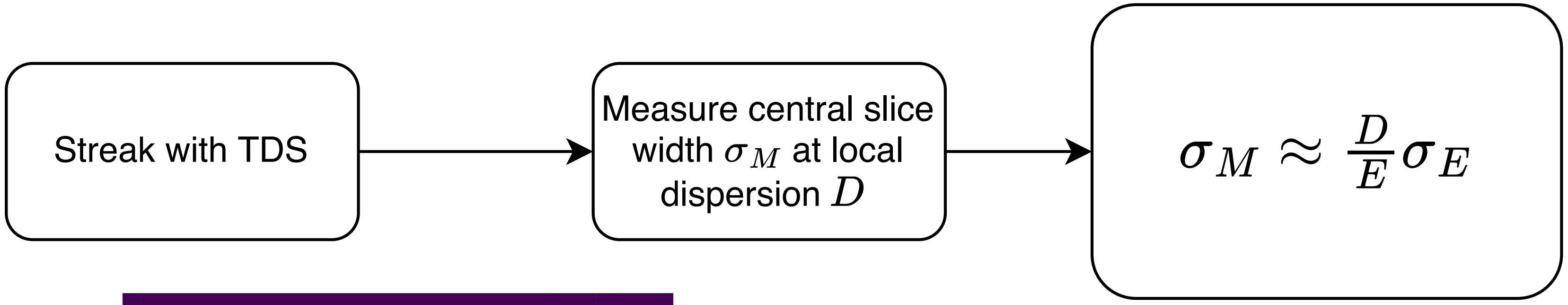
Only provides an upper limit on uncorrelated spread σ_E

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!

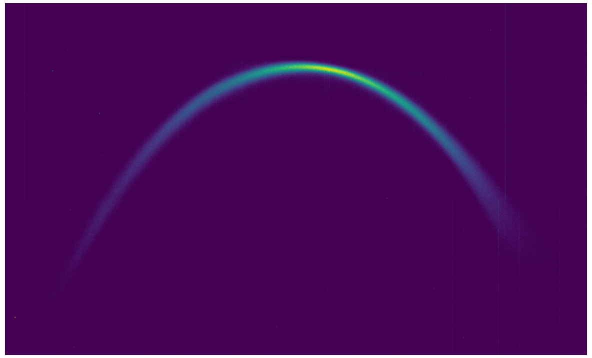
Need to separate these effects...



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:

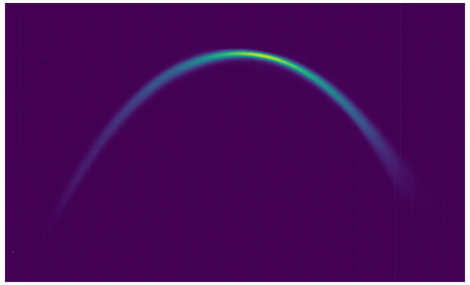
$$\sigma_{E_{\text{final}}}^2 = \sigma_E^2 + (ekV)^2 \underbrace{\sigma_I^2}_{\text{Beamsize in the TDS}}$$

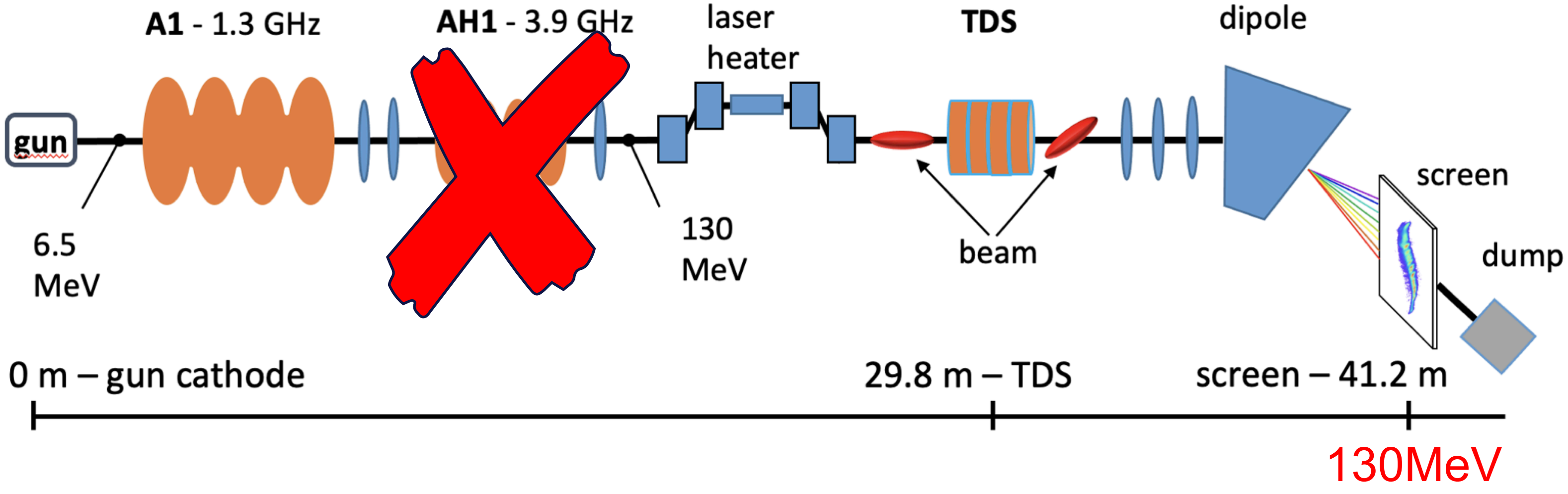
$$\sigma_M^2 = \underbrace{\sigma_R^2}_{\text{Imaging resolution}} + \underbrace{\sigma_B^2}_{\text{Betatron}} + \underbrace{\frac{D^2}{E^2}\sigma_E^2}_{\text{energy spread contribution}} + \underbrace{\frac{D^2}{E^2}(ekV)^2\sigma_I^2}_{\text{TDS contribution}}$$

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

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

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

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

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

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

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

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

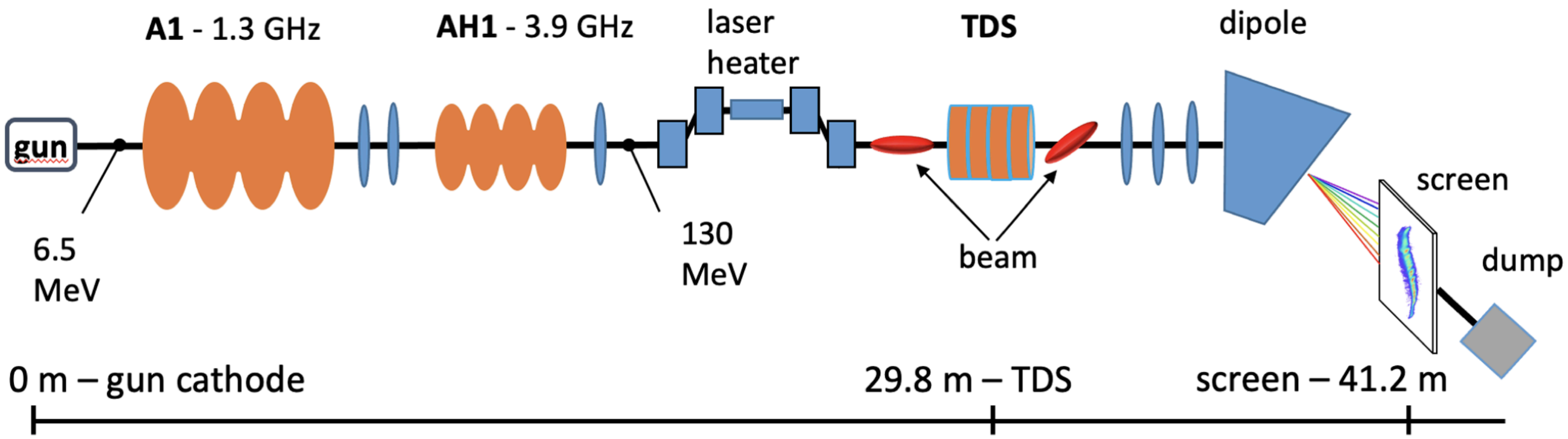
$$\sigma_B = \sqrt{B_\beta \beta_x^0}$$

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

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

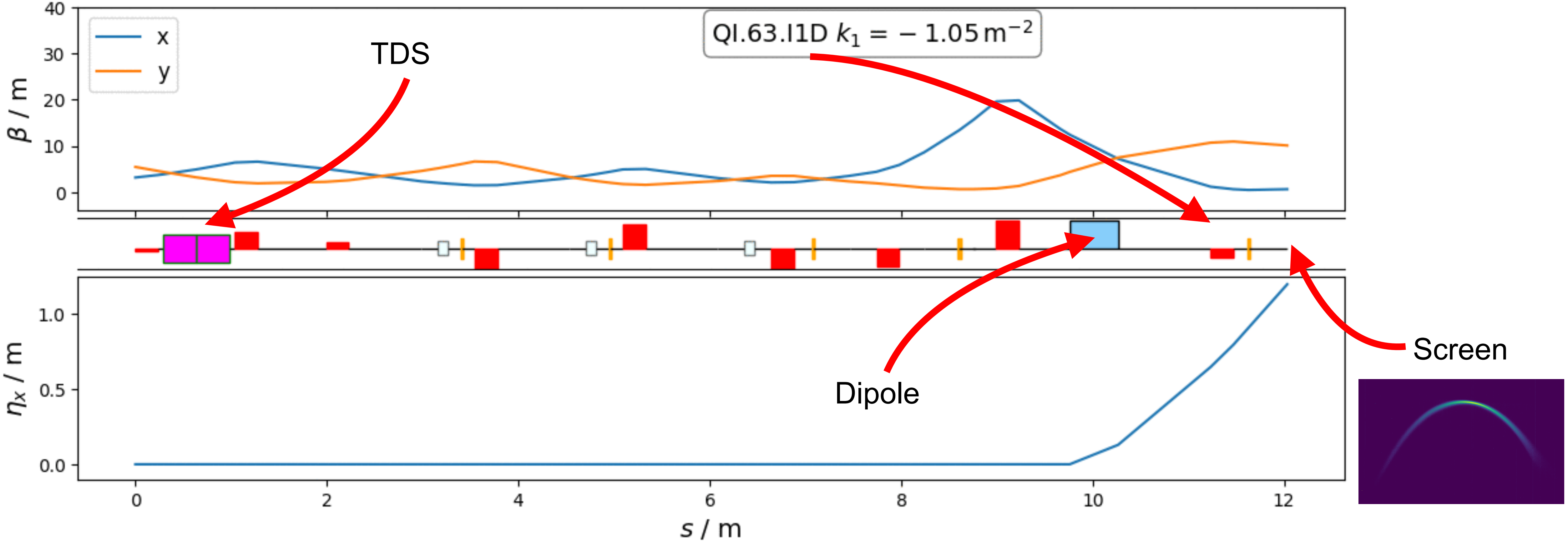
Setting up the Injector for Slice Energy Spread Measurements

- ✓ 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 130MeV at the screen.
- ✓ Turn laser heater off.
- ✓ Apply **special optics** (larger D at screen with a fixed, small beta).
- ✓ Match central slice.
- ✓ Measure the dispersion.



Special optics for measurement from TDS to the screen

Optics developed by Nina



TDS

Dipole

Screen

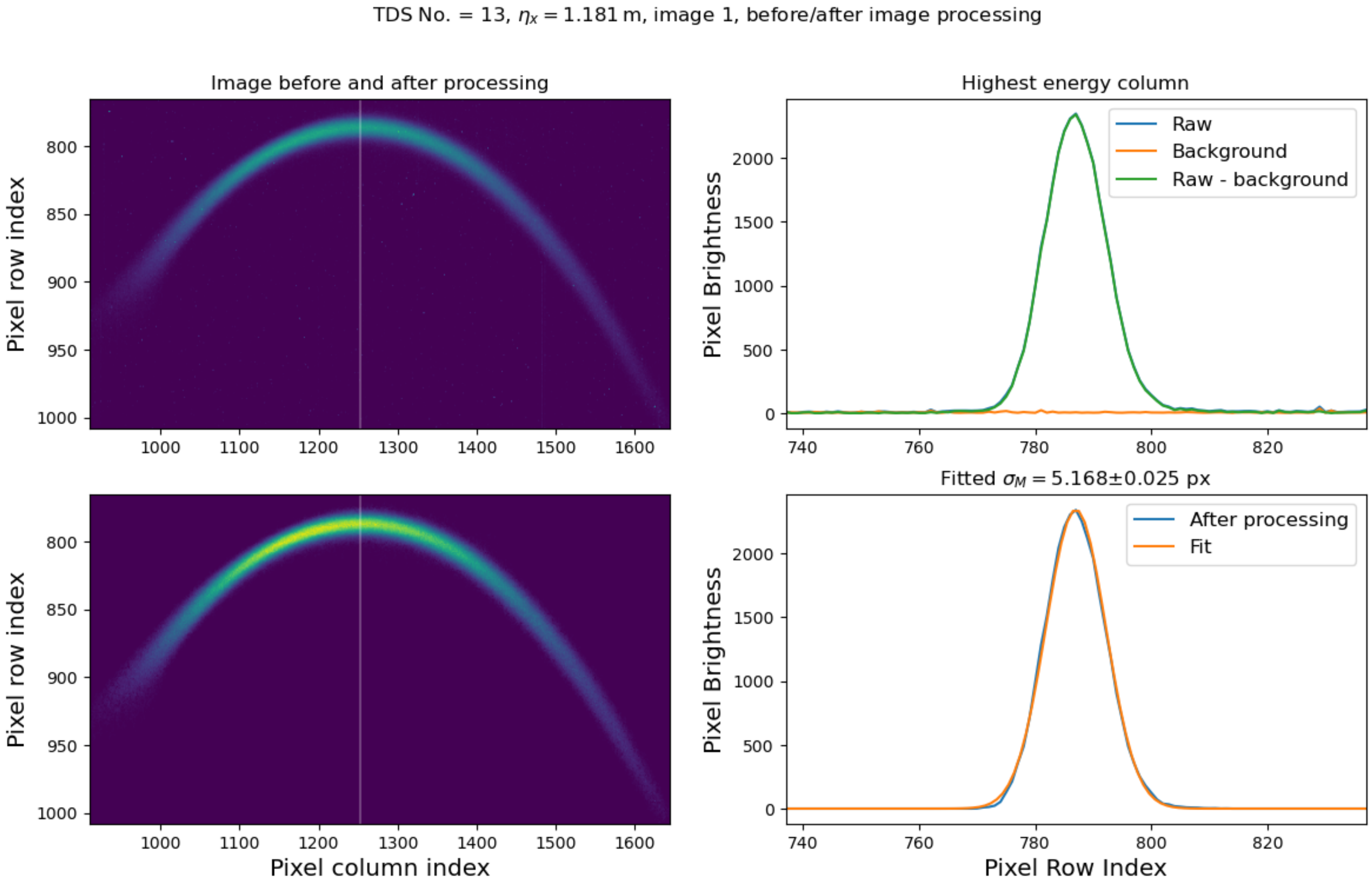
Measurement procedure

Take 30 beam images and 5 background images:

- ➡ at each voltage in TDS scan
- ➡ and each dispersion in dispersion scan

Then:

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

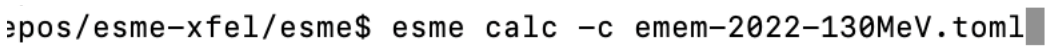


Validated in simulations to work:
➡ 10.1103/PhysRevAccelBeams.24.064201

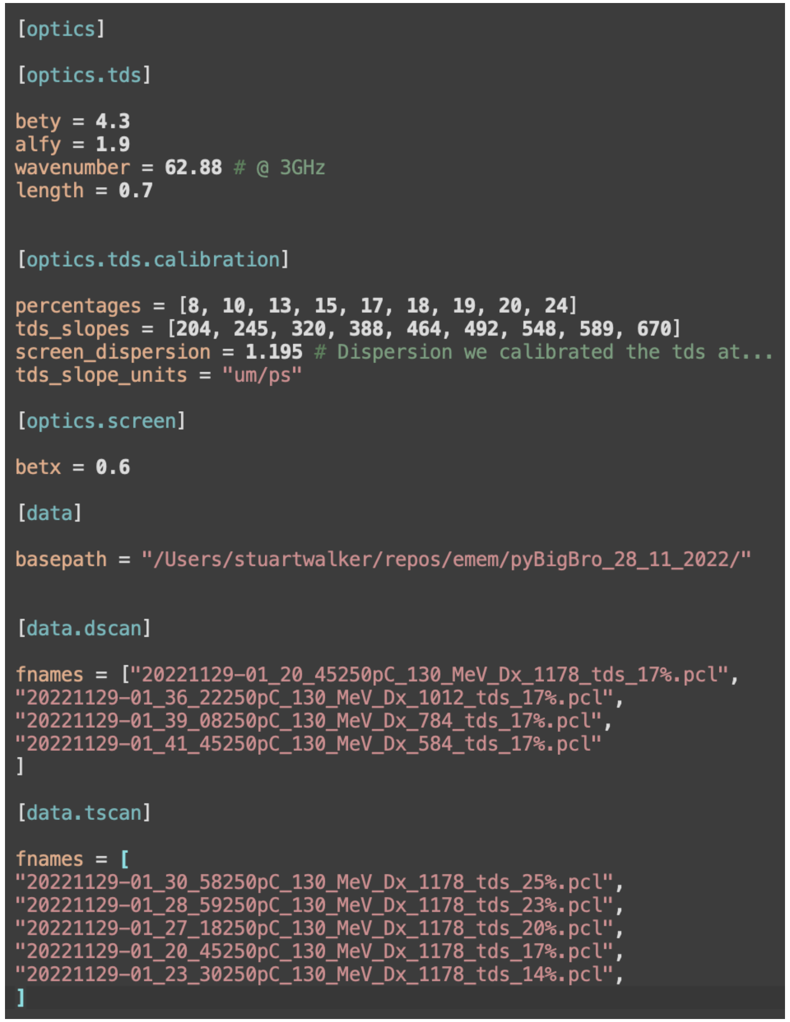
New analysis

Implemented a new analysis tool based on the dispersion/TDS scan method:

- ➡ Aims to be fast and simple to run, allowing for *analysis* in the control room.
- ➡ Quick results (before: analyse data the next day).
- ➡ Input: Simple markup file giving locations of image files and information about the TDS.
- ➡ Outputs: Full suite of analysis plots for every image, every scan data point, and, of course, the energy spread, among others



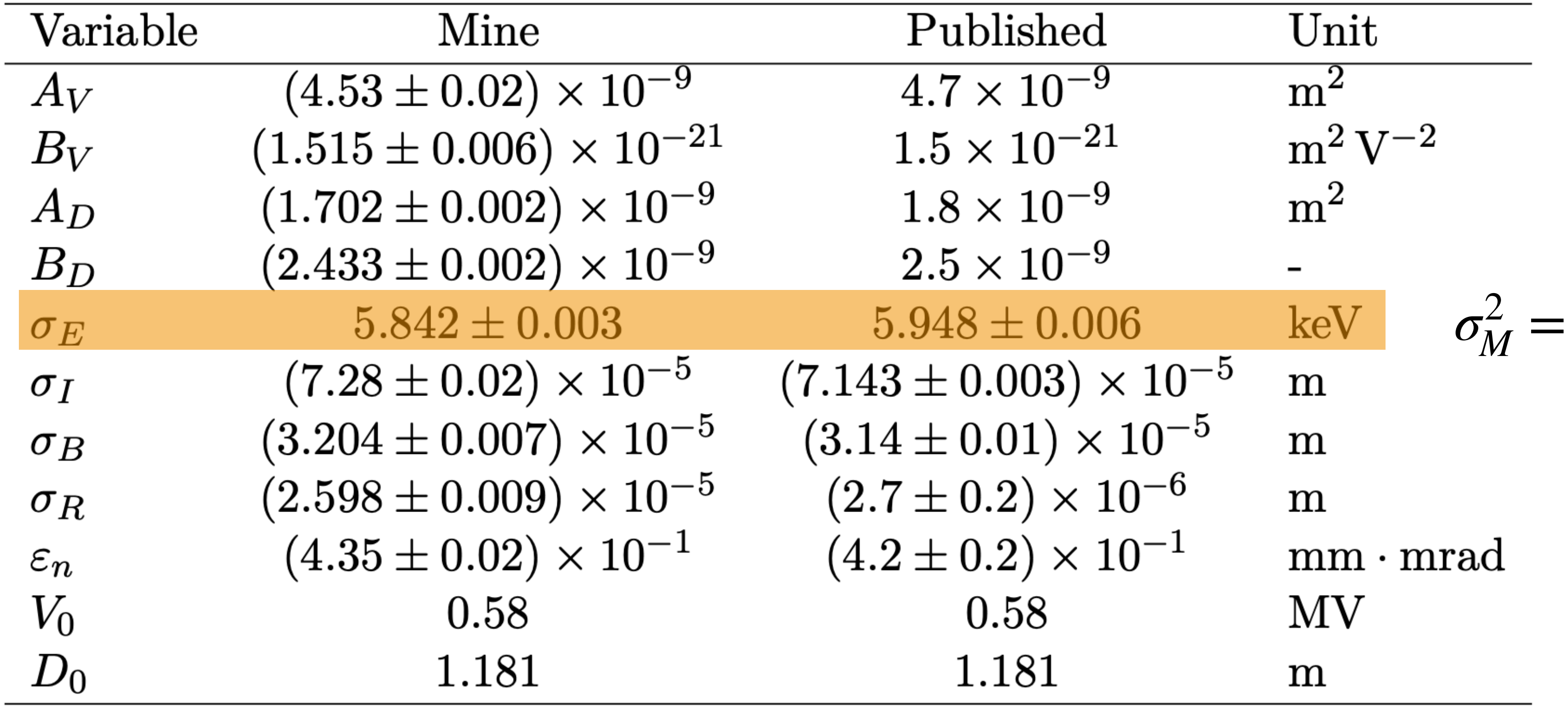
```
epos/esme-xfel/esme$ esme calc -c emem-2022-130MeV.toml
```



```
[optics]

[optics.tds]

bety = 4.3
alfy = 1.9
wavenumber = 62.88 # @ 3GHz
length = 0.7


[optics.tds.calibration]

percentages = [8, 10, 13, 15, 17, 18, 19, 20, 24]
tds_slopes = [204, 245, 320, 388, 464, 492, 548, 589, 670]
screen_dispersion = 1.195 # Dispersion we calibrated the tds at...
tds_slope_units = "um/ps"

[optics.screen]

betx = 0.6

[data]

basepath = "/Users/stuartwalker/repos/emem/pyBigBro_28_11_2022/"


[data.dscan]

fnames = ["20221129-01_20_45250pC_130_MeV_Dx_1178_tds_17%.pcl",
"20221129-01_36_22250pC_130_MeV_Dx_1012_tds_17%.pcl",
"20221129-01_39_08250pC_130_MeV_Dx_784_tds_17%.pcl",
"20221129-01_41_45250pC_130_MeV_Dx_584_tds_17%.pcl"
]

[data.tscan]

fnames = [
"20221129-01_30_58250pC_130_MeV_Dx_1178_tds_25%.pcl",
"20221129-01_28_59250pC_130_MeV_Dx_1178_tds_23%.pcl",
"20221129-01_27_18250pC_130_MeV_Dx_1178_tds_20%.pcl",
"20221129-01_20_45250pC_130_MeV_Dx_1178_tds_17%.pcl",
"20221129-01_23_30250pC_130_MeV_Dx_1178_tds_14%.pcl",
]
```

Results in < 1 minute

New Analysis Tool Validation against published February 2021 results



Variable	Mine	Published	Unit
A_V	$(4.53 \pm 0.02) \times 10^{-9}$	4.7×10^{-9}	m^2
B_V	$(1.515 \pm 0.006) \times 10^{-21}$	1.5×10^{-21}	$\mathrm{m}^2\,\mathrm{V}^{-2}$
A_D	$(1.702 \pm 0.002) \times 10^{-9}$	1.8×10^{-9}	m^2
B_D	$(2.433 \pm 0.002) \times 10^{-9}$	2.5×10^{-9}	-
σ_E	5.842 ± 0.003	5.948 ± 0.006	keV
σ_I	$(7.28 \pm 0.02) \times 10^{-5}$	$(7.143 \pm 0.003) \times 10^{-5}$	m
σ_B	$(3.204 \pm 0.007) \times 10^{-5}$	$(3.14 \pm 0.01) \times 10^{-5}$	m
σ_R	$(2.598 \pm 0.009) \times 10^{-5}$	$(2.7 \pm 0.2) \times 10^{-6}$	m
ε_n	$(4.35 \pm 0.02) \times 10^{-1}$	$(4.2 \pm 0.2) \times 10^{-1}$	$\mathrm{mm} \cdot \mathrm{mrad}$
V_0	0.58	0.58	MV
D_0	1.181	1.181	m

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

28th November 2022 Measurements

Aim:

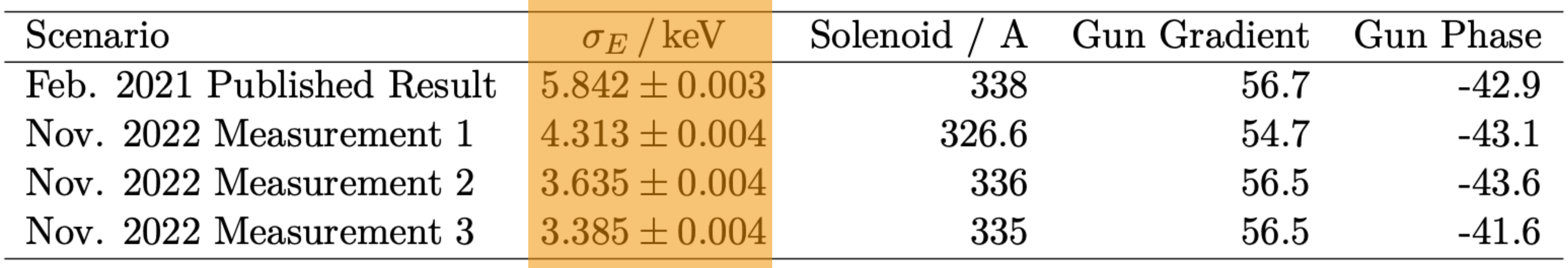
- Repeat measurement from 2021 publication.
- Match beamline configuration from that time as much as possible.
- Particular attention to:
    - Gun gradient: 54.7
    - Solenoid: 326A
- **Cathode changed this year!**

Outcome:

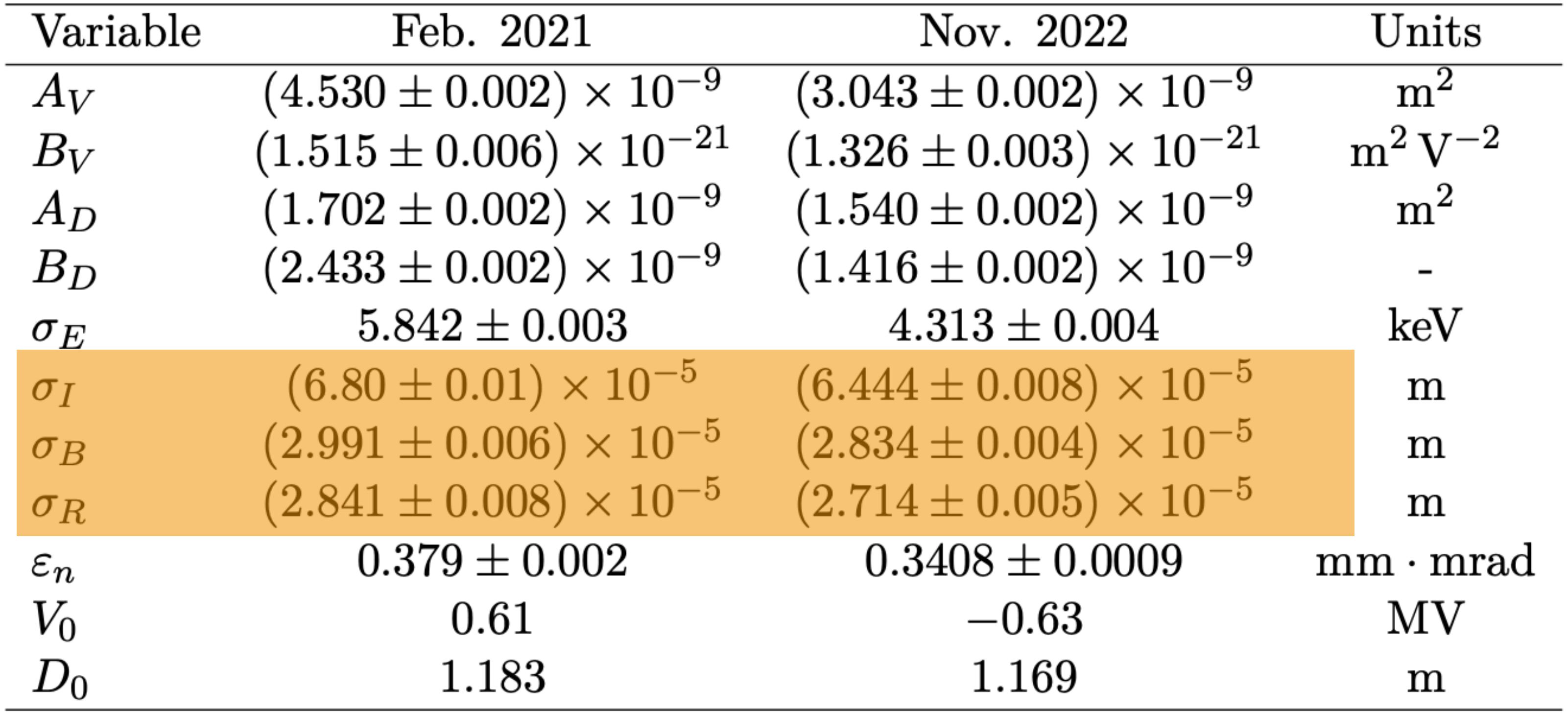
- Three energy spread measurements over 8 hours:

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

Results



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



Variable	Feb. 2021	Nov. 2022	Units
A_V	$(4.530 \pm 0.002) \times 10^{-9}$	$(3.043 \pm 0.002) \times 10^{-9}$	m^2
B_V	$(1.515 \pm 0.006) \times 10^{-21}$	$(1.326 \pm 0.003) \times 10^{-21}$	$\mathrm{m}^2\,\mathrm{V}^{-2}$
A_D	$(1.702 \pm 0.002) \times 10^{-9}$	$(1.540 \pm 0.002) \times 10^{-9}$	m^2
B_D	$(2.433 \pm 0.002) \times 10^{-9}$	$(1.416 \pm 0.002) \times 10^{-9}$	-
σ_E	5.842 ± 0.003	4.313 ± 0.004	keV
σ_I	$(6.80 \pm 0.01) \times 10^{-5}$	$(6.444 \pm 0.008) \times 10^{-5}$	m
σ_B	$(2.991 \pm 0.006) \times 10^{-5}$	$(2.834 \pm 0.004) \times 10^{-5}$	m
σ_R	$(2.841 \pm 0.008) \times 10^{-5}$	$(2.714 \pm 0.005) \times 10^{-5}$	m
ε_n	0.379 ± 0.002	0.3408 ± 0.0009	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, solenoid 326A, gun phase -43 (most similar to 2021 result)
2. Gun gradient to 56.5, solenoid to 336A,
3. Solenoid to 335A, gun phase to -41.

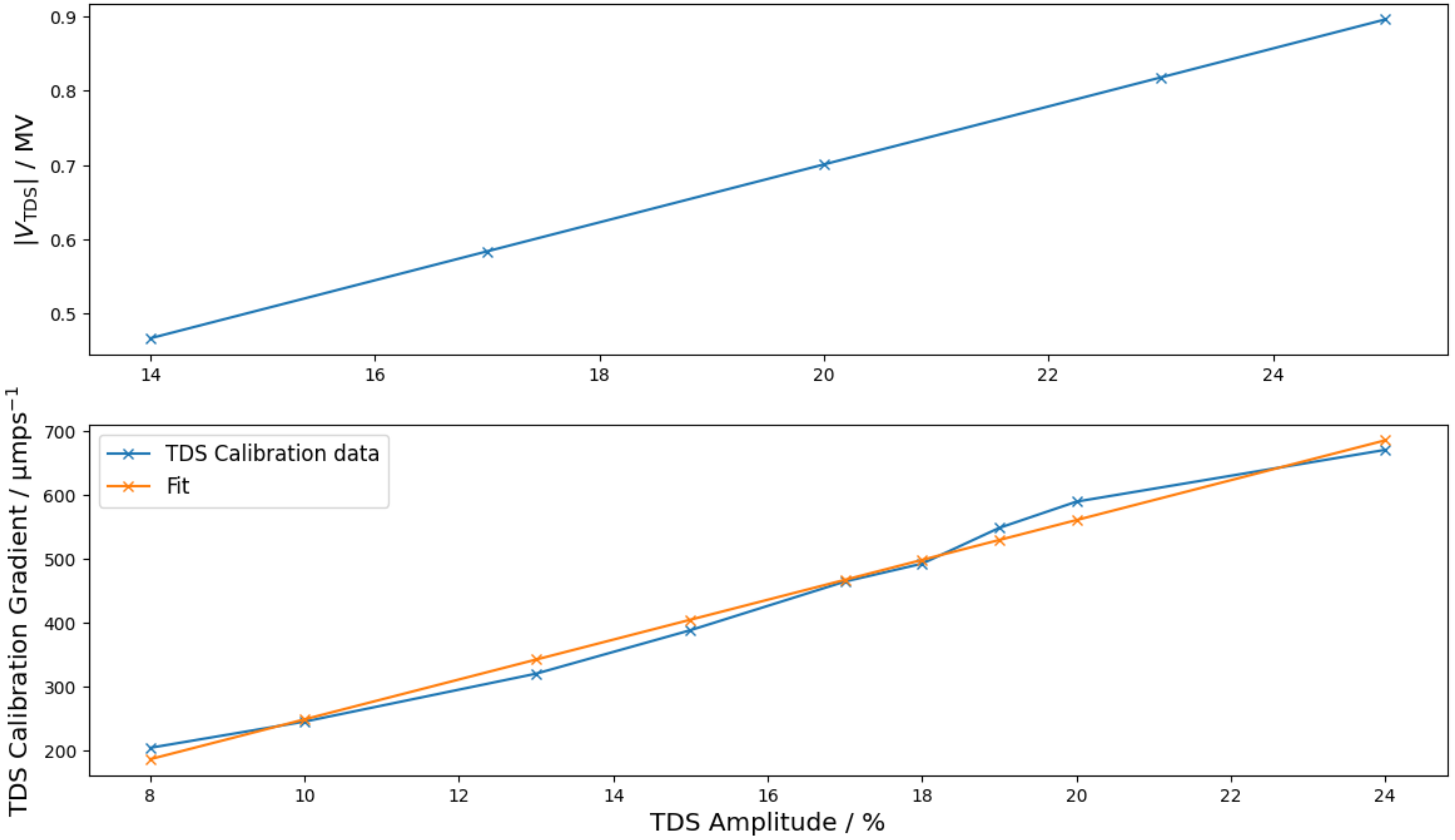
Measurement details

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

TDS Calibration 28th November 2022

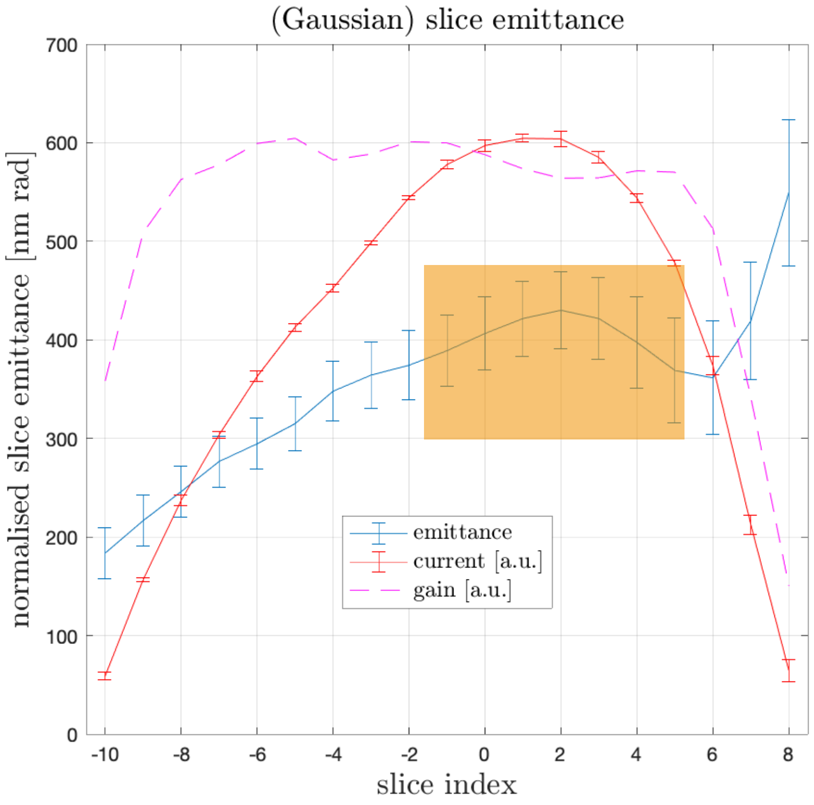
- Measure $\frac{\mathrm{d}\langle\Delta y\rangle}{\mathrm{d}t}$ at a range of "amplitudes" up front.
- Then use this curve henceforth to determine the slope (and ultimately the TDS voltage) for all scan datapoints.
- Faster than measuring each time but still difficult.

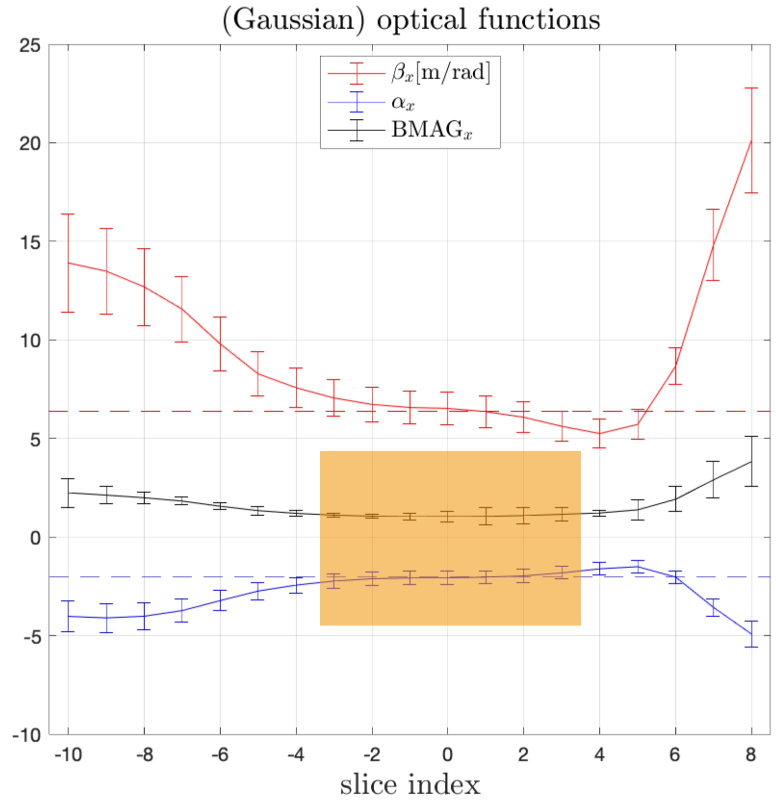
TDS Calibration data we took beforehand (below) and applied to scan (above)



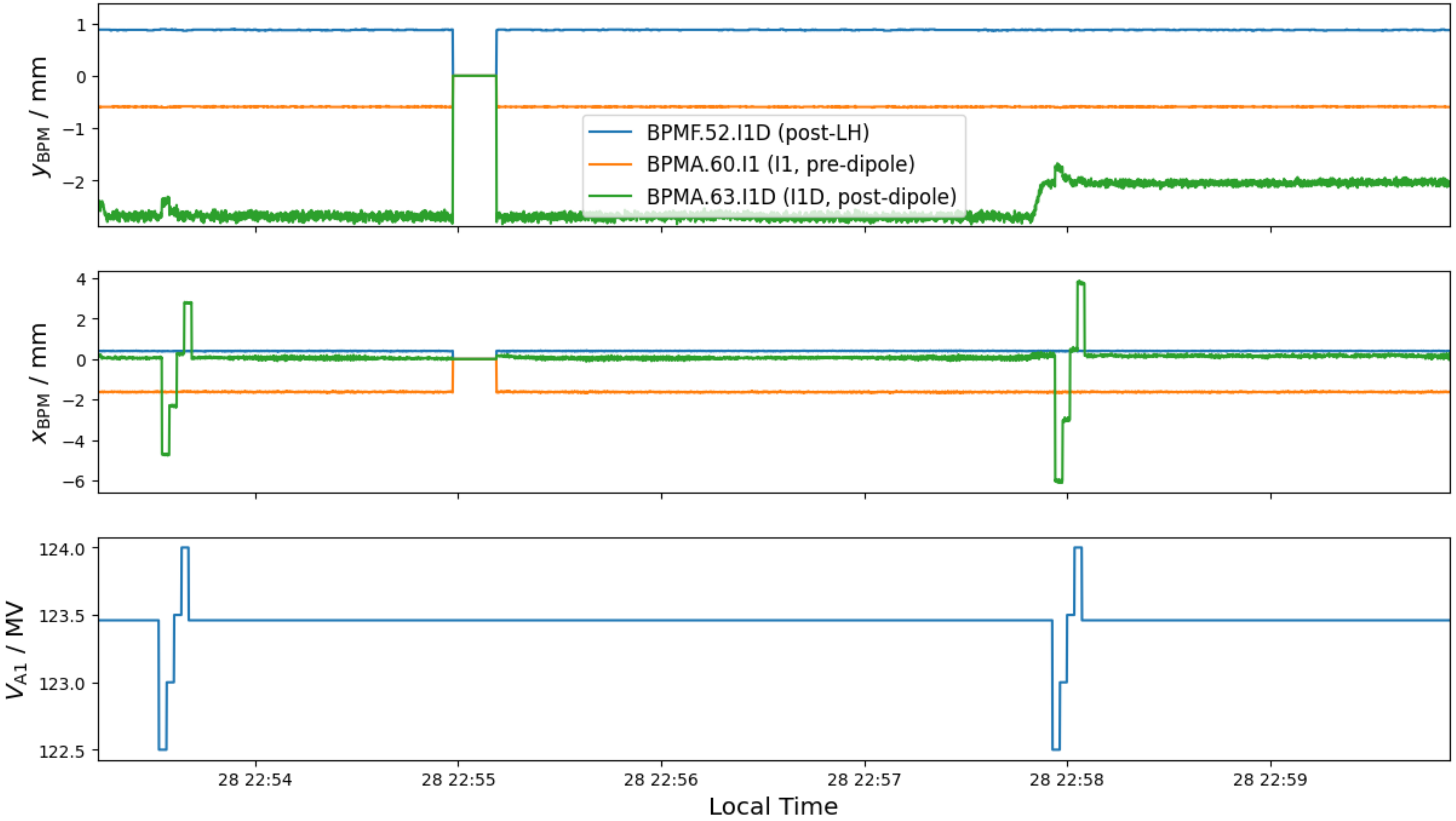
Beam matching

- 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.

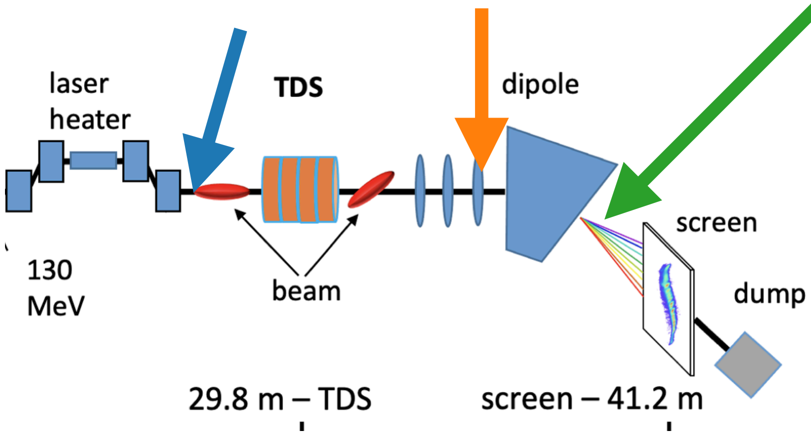




Do we get a kick from A1 when measuring the dispersion?



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

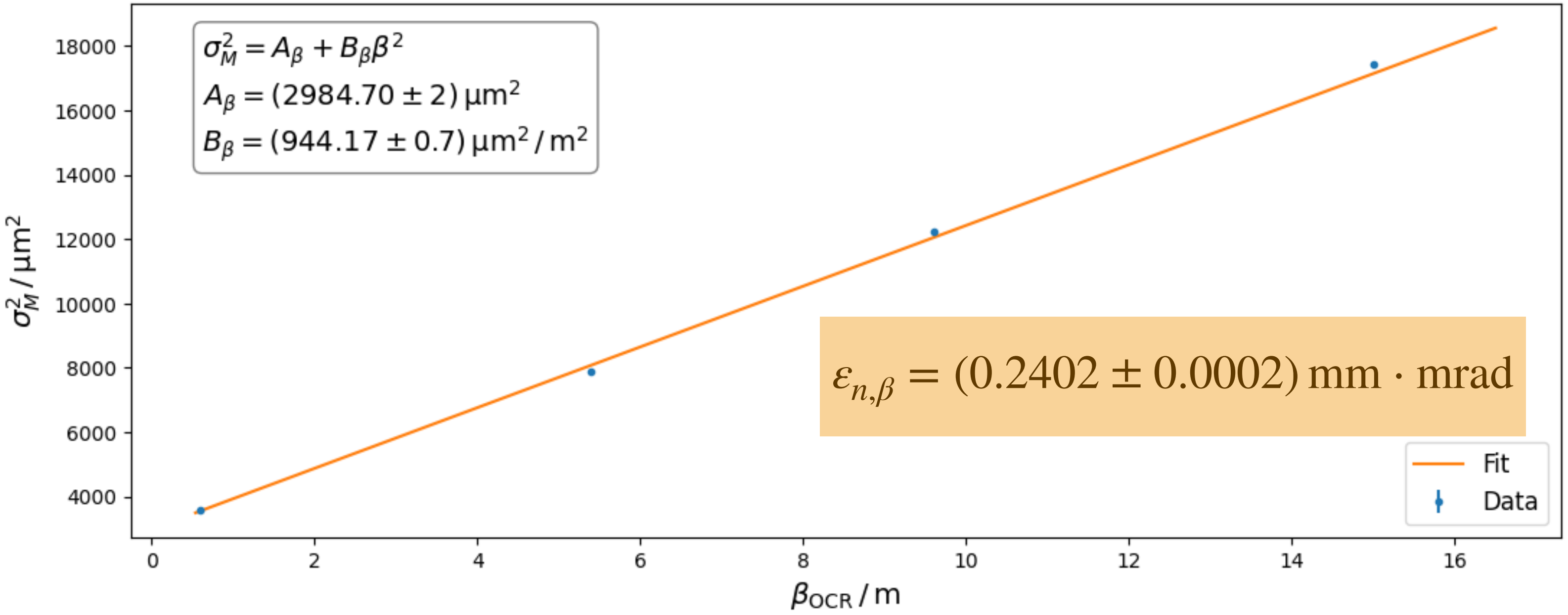


Beta Scan

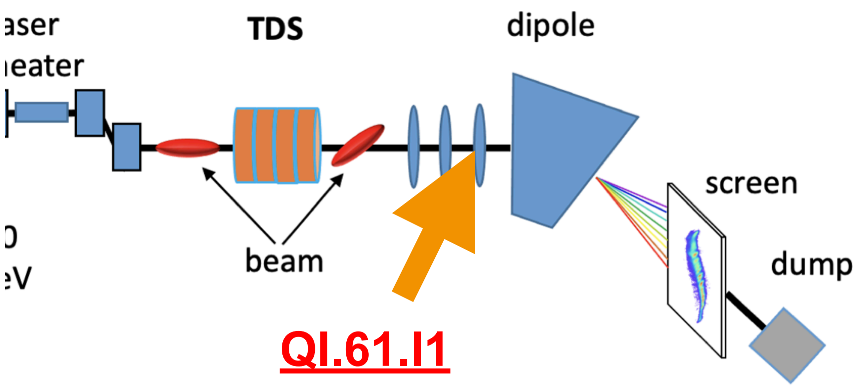
- ➡ Can also measure the emittance by scanning beta
- ➡ We know the beta function at the TDS and therefore at the screen by linear optics.
- ➡ Scan QI.61.I1 (before dipole) to vary β without changing *D*.

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

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



$$\varepsilon_{n,\beta} = (0.2402 \pm 0.0002)\,\text{mm}\cdot\text{mrad}$$



Consistency of results

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

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

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

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

➡ What I've used so far:

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

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

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

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

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

➡ Alternative functions:

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

$$\sigma_I = \frac{E_0}{D_0 ek V_0}\sqrt{D_0^2 B_D + A_D - A_V}$$

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

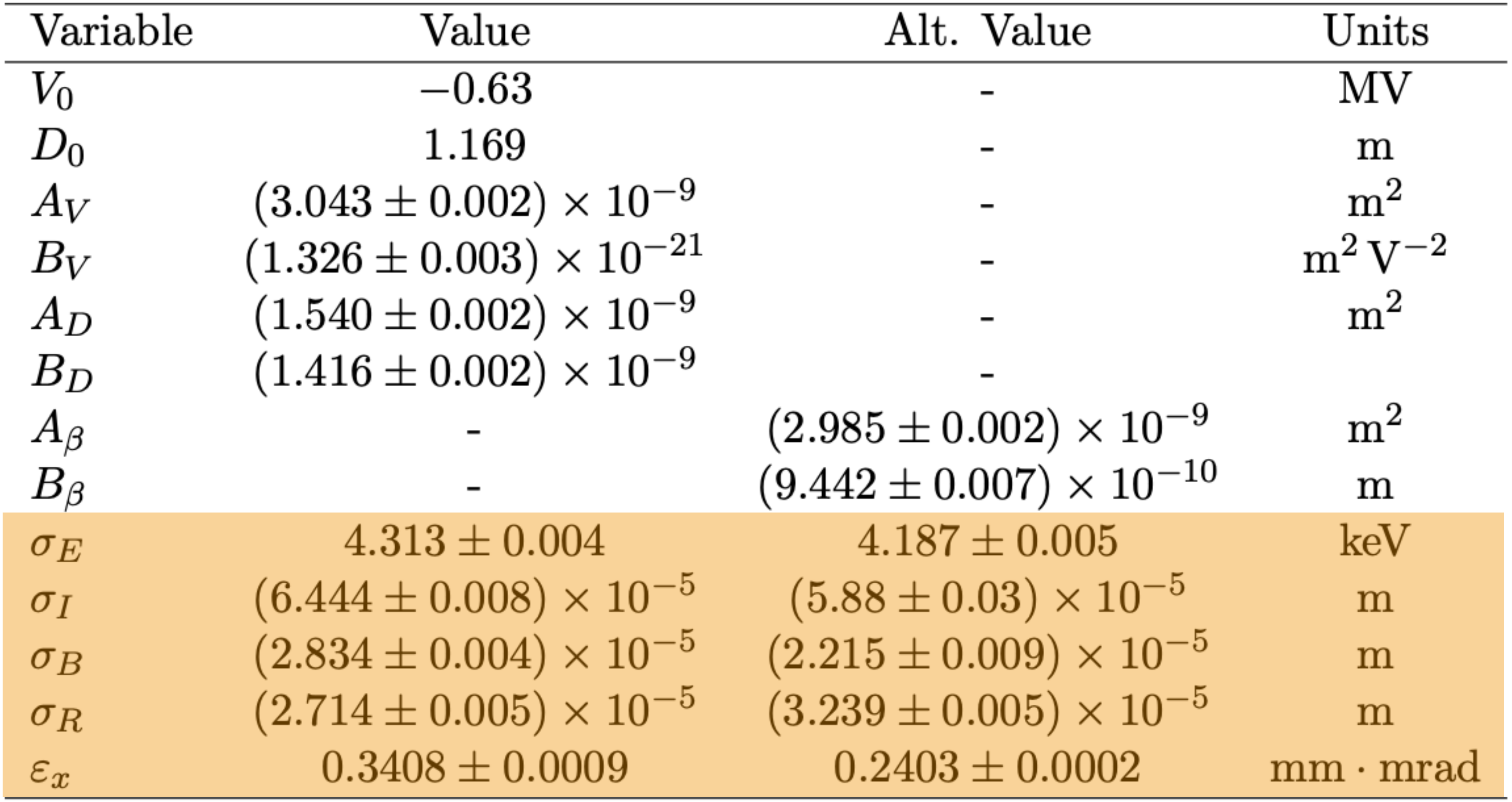
$$B_\beta = \varepsilon_n \gamma_0^{-1}$$

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

➡ Both should be equivalent!

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)

Conclusion

- ➡ The measured energy spread in the injector has decreased since Feb. 2021 **from 5.8keV to 4.2keV**.
- ➡ Still not the value predicted by theory (Erion's simulations predict ≈2keV with IBS).
- ➡ In this period only the cathode has changed, or maybe something else.
- ➡ Suggests some long term drift in the energy spread.
- ➡ Hints at relationship between solenoid and gun configuration and energy spread shown.
- ➡ Ideally would continue to monitor the energy spread over time and further establish relationship.
  - ➡ Needs to be faster, could be done in <5mins in principle, but needs more code development.

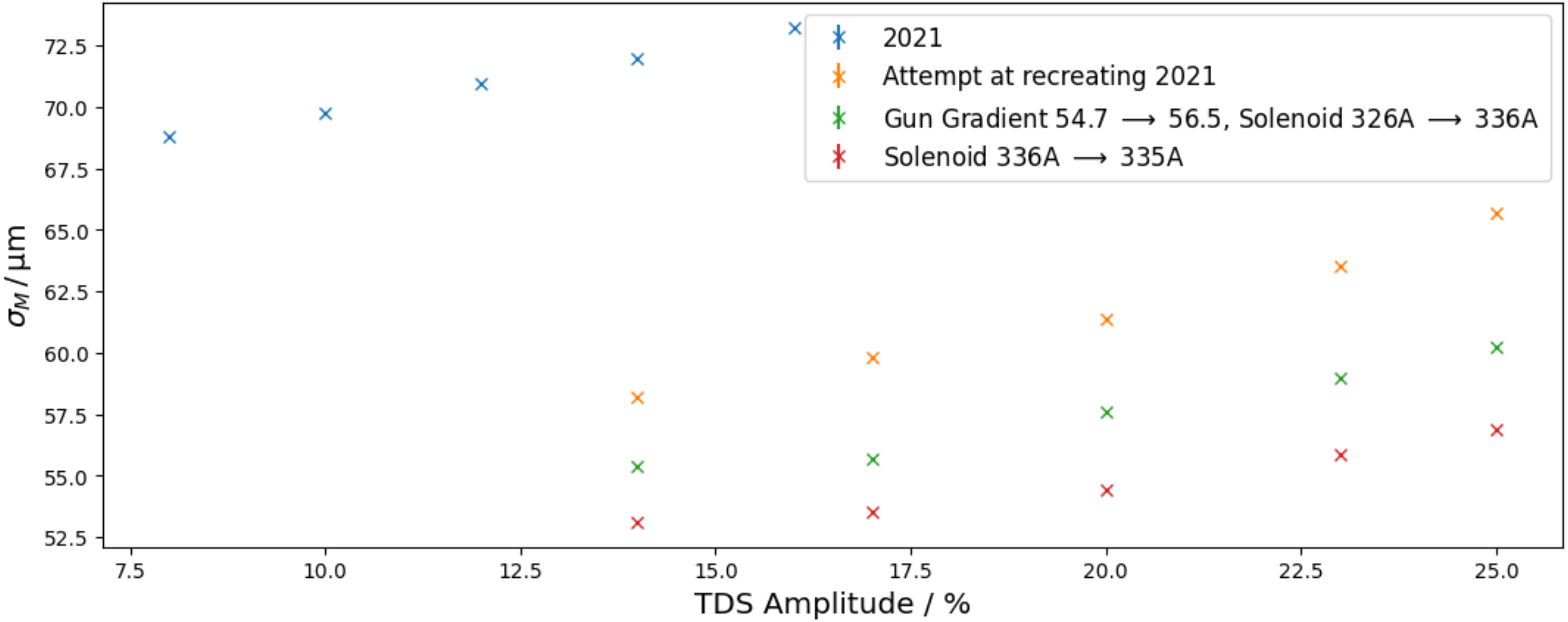
Outlook

- ➡ Controlling and measuring energy spread is important.
    - ➡ Measurement could be used to calibrate laser heater.
    - ➡ Know gun/injector condition more precisely.
    - ➡ Boost reproducibility in the machine.
- ➡ Need more diagnostics after each shutdown/blue week to see changes as they happen.
- ➡ Currently simply takes too long: setup time: >2 hours, taking data: (0.5-1)hr per measurement.
    - ➡ Analysis has been sped up to take <1 minute. Data taking could take < 5 minutes $\Longrightarrow$ requires code development.
- ➡ Measurement procedure could be extended to BC2:
    - ➡ Unique opportunity at the EuXFEL to directly measure intrabeam scattering in an FEL.

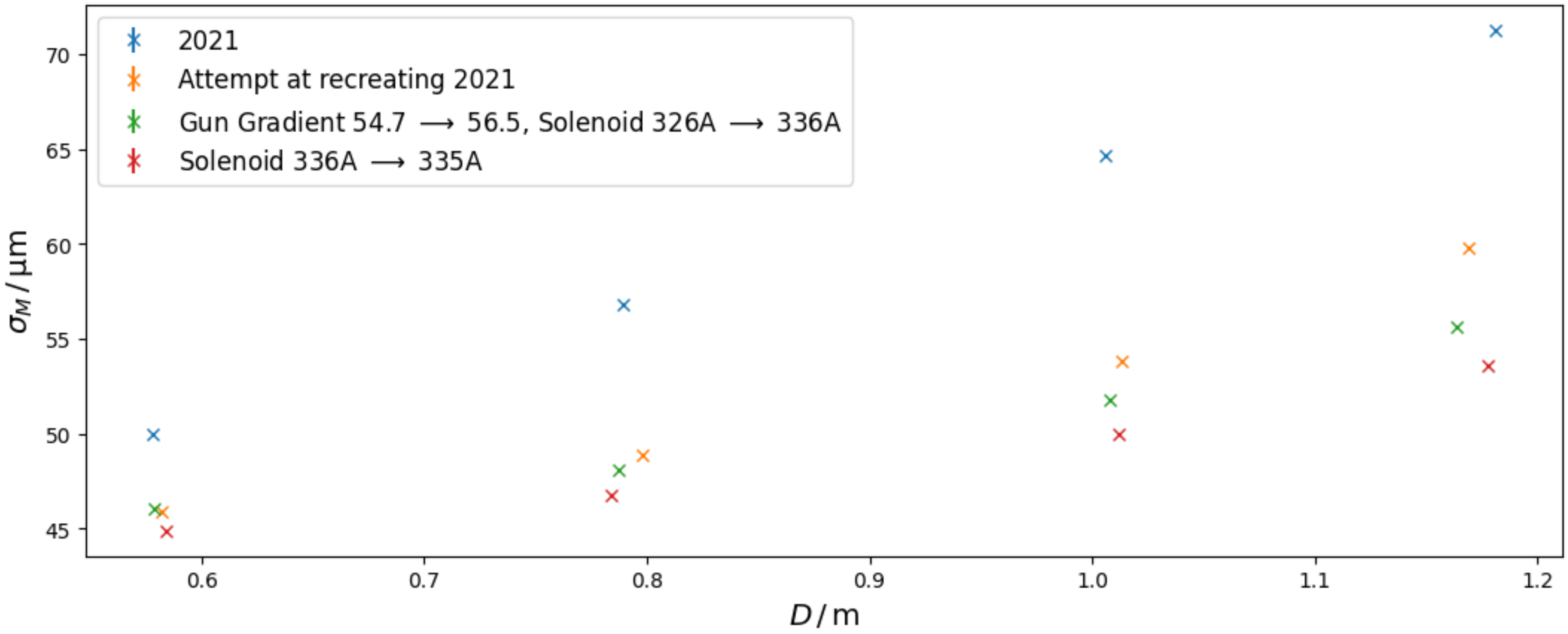
Final Slide

- Thanks also to:
    - Bolko (TDS calibration + support)
    - Matthias (fast/reliable matching tool + support)
    - Frank (beam energy coming out of the gun measurement)
    - Torsten (useful and interesting conversations regarding laser heater)
- Questions?

Central Pixel Widths in the TDS Voltage Scans



Central Pixel Widths in the Dispersion Scans

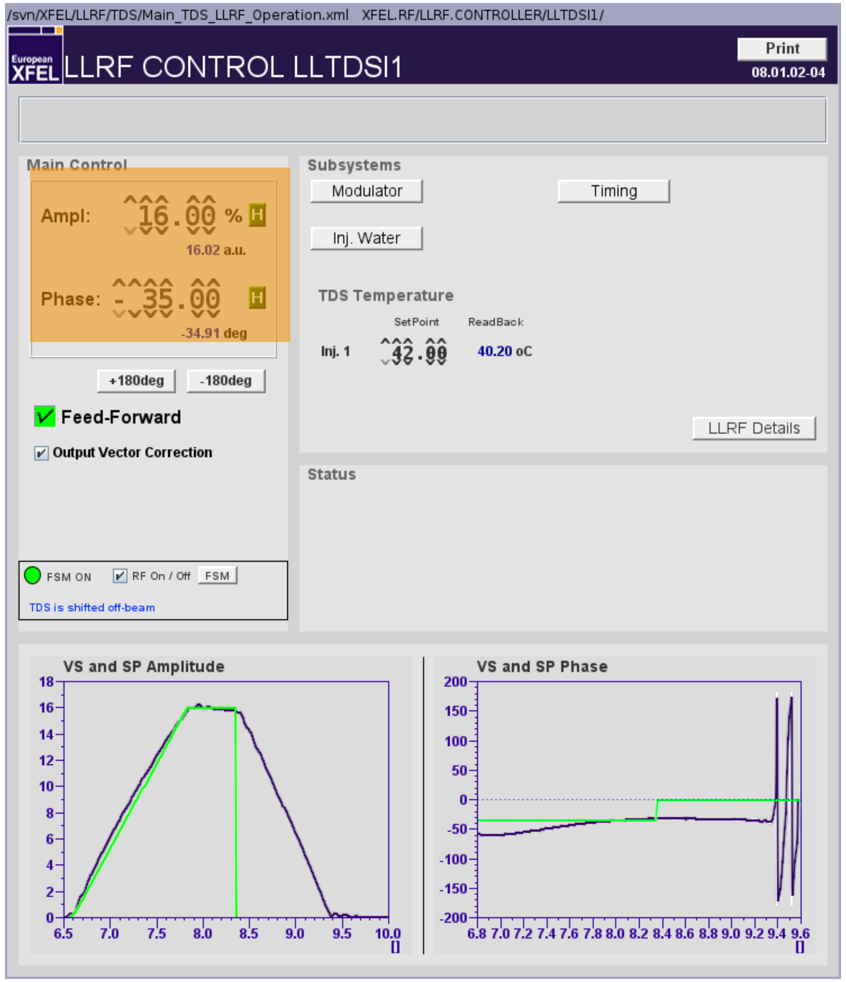


➡ Same for TDS voltage scan

TDS Calibration

TDS Knobs:

- ➡ Phase
- ➡ Amplitude in %
  - ➡ Need this in volts!
  - ➡ Actually not that easy...



/svn/XFEL/LLRF/TDS/Main_TDS_LLRF_Operation.xml XFEL.RF/LLRF.CONTROLLER/LLTDSI1/

LLRF CONTROL LLTDSI1

08.01.02-04

Main Control

Ampl: 16.00 %

16.02 a.u.

Phase: -35.00

-34.91 deg

☑ Feed-Forward

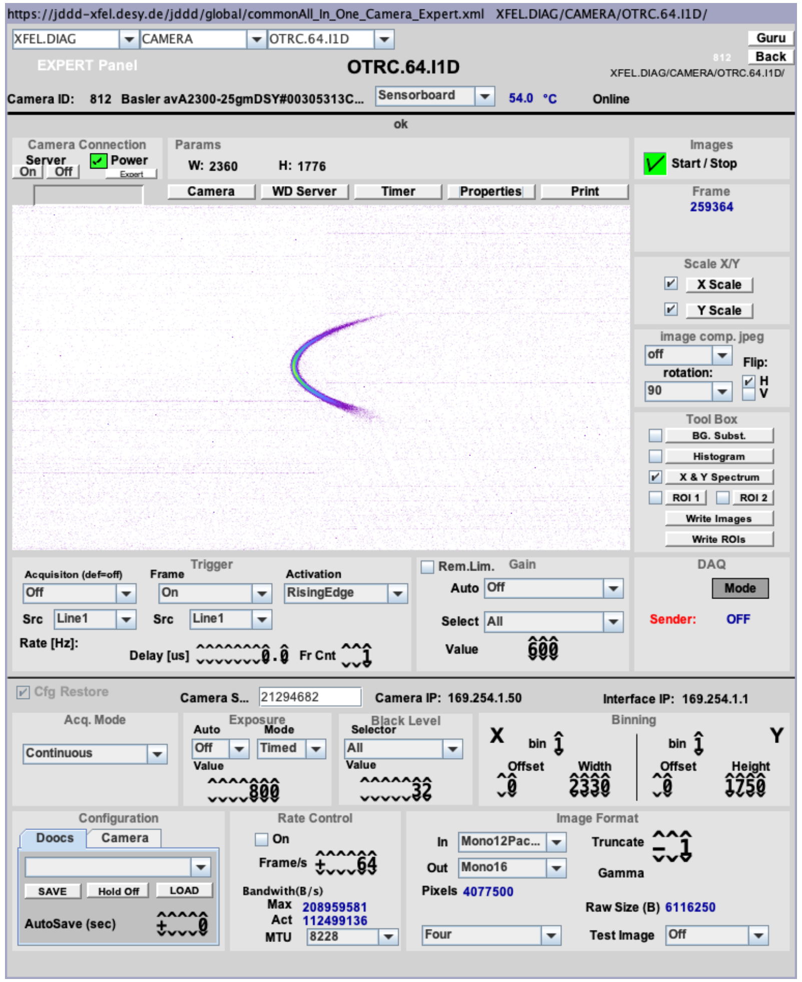
☑ Output Vector Correction

● FSM ON ☑ RF On / Off

TDS is shifted off-beam

TDS Temperature

	SetPoint	ReadBack
Inj. 1	42.00	40.20 oC



https://jddd-xfel.desy.de/jddd/global/commonAll_In_One_Camera_Expert.xml XFEL.DIAG/CAMERA/OTRC.64.I1D/

XFEL.DIAG / CAMERA / OTRC.64.I1D

OTRC.64.I1D

XFEL.DIAG/CAMERA/OTRC.64.I1D/

Camera ID: 812 Basler avA2300-25gmDSY#00305313C... Sensorboard 54.0 °C Online

ok

Params W: 2360 H: 1776

Frame 259364

image comp. jpeg: off

rotation: 90

Flip: ☑ H ☐ V

☑ X Scale ☑ Y Scale

☐ BG. Subst. ☐ Histogram ☑ X & Y Spectrum ☐ ROI 1 ☐ ROI 2

Acquisiton (def=off): Off

Trigger Frame: On

Activation: RisingEdge

Src: Line1 Src: Line1

Delay [us] 0.0 Fr Cnt 1

☐ Rem.Lim.

Gain Auto: Off

Select: All

Value 600

Sender: OFF

☑ Cfg Restore

Camera S... 21294682 Camera IP: 169.254.1.50 Interface IP: 169.254.1.1

Acq. Mode: Continuous

Exposure Auto: Off Mode: Timed Value 800

Black Level Selector: All Value 32

Binning X bin 1 Offset 0 Width 2330 | Y bin 1 Offset 0 Height 1750

Rate Control ☐ On Frame/s 64

Bandwith(B/s) Max 208959581 Act 112499136

MTU 8228

Image Format In: Mono12Pac... Out: Mono16

Truncate 1

Gamma

Pixels 4077500

Raw Size (B) 6116250

Four

Test Image: Off

AutoSave (sec) 0

European XFEL

HELMHOLTZ GEMEINSCHAFT

DESY

TDS Calibration

$$\langle \Delta y \rangle = \frac{eV_0}{E}\sqrt{\beta_y \beta_y^0}\sin\Delta\mu_y \sin\psi = \frac{eV_0}{E}R_{34}\sin\psi$$

$$V = V_0 \sin\psi = V_0 \sin(\omega t)$$

$$\frac{\mathrm{d}\langle \Delta \mathrm{y} \rangle}{\mathrm{dt}} = \frac{eV_0}{E}R_{34}\omega\cos\omega t \approx \frac{eV_0}{E}R_{34}\omega$$

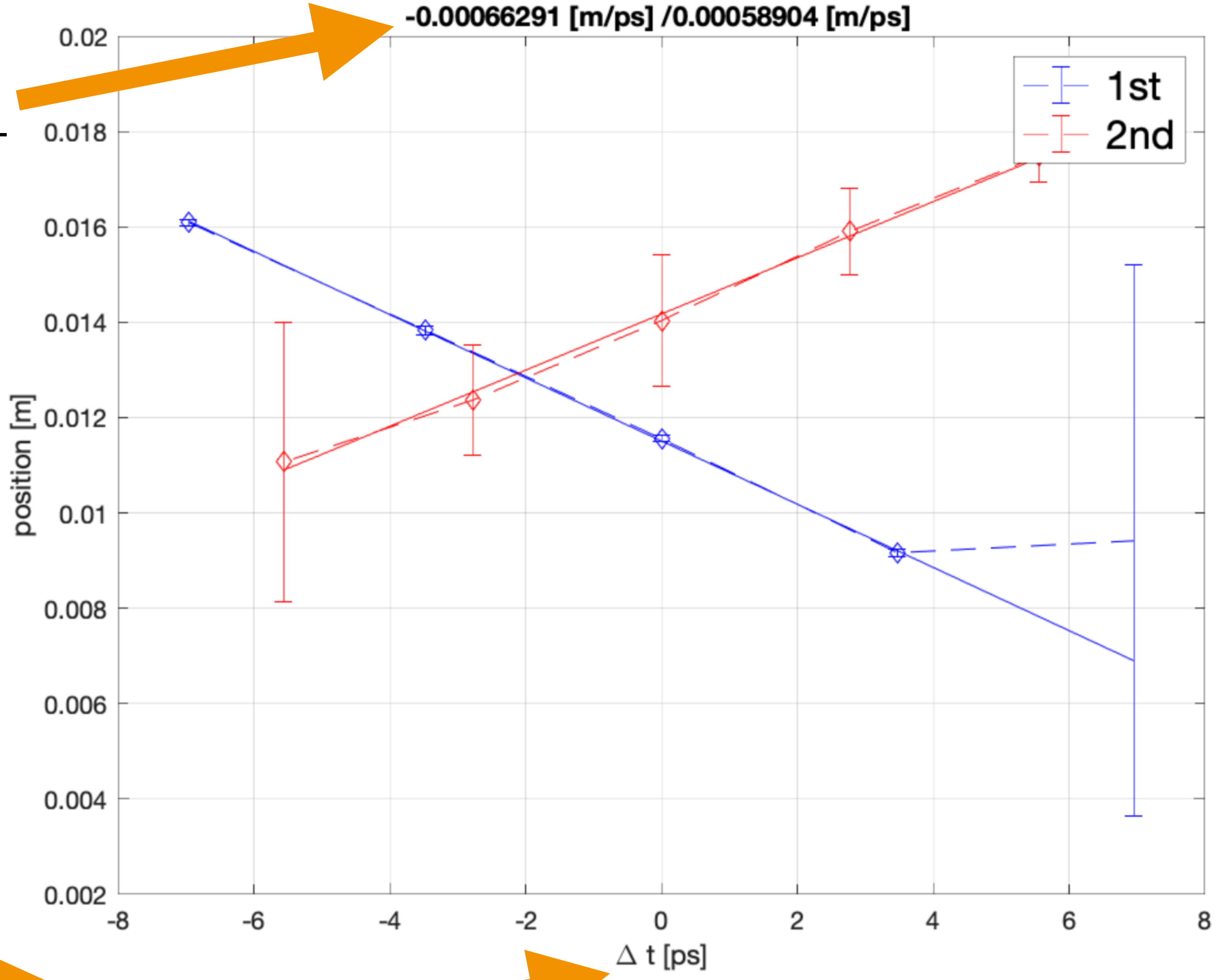
$$V_0 = \frac{E}{e\omega R_{34}}\frac{\mathrm{d}\langle \Delta \mathrm{y} \rangle}{\mathrm{dt}}$$

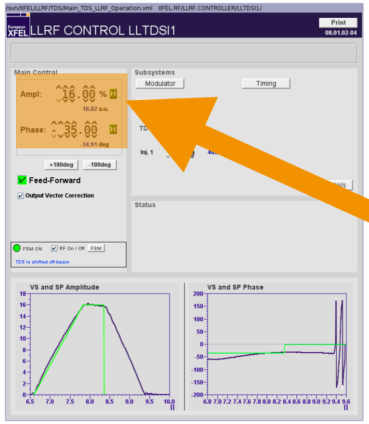
$$\frac{\mathrm{d}\langle \Delta \mathrm{y} \rangle}{\mathrm{dt}}$$

$$\langle \Delta y \rangle$$

$$\psi$$

Courtesy of Bolko and his tool




/svn/XFEL/LLRF/TDS/Main_TDS_LLRF_Operation.xml XFEL.RF/LLRF.CONTROLLER/LLTDSI1/

LLRF CONTROL LLTDSI1

08.01.02-04

Ampl: 16.00 %

16.02 a.u.

Phase: -35.00

-34.91 deg

☑ Feed-Forward

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