Slice energy spread measurement in the low energy injector at PITZ

Preliminary results

Houjun Qian, Mikhail Krasilnikov, Anusorn Lueangaramwong, Xiangkun Li, Osip Lishilin
6.04.2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Slice energy spread measurement

Low energy vs high energy

- Slice energy spread measurement by TDS + dipole

$$\sigma_M^2 = \sigma_{scr}^2 + \sigma_{emit}^2 + \left(D\frac{\sigma_E}{E}\right)^2 + \left(D\frac{\sigma_{TDS}}{E}\right)^2$$

- Dipole resolution
  - Energy resolution by screen: $\frac{\sigma_{scr}}{D}\gamma$
  - Energy resolution by emittance: $\frac{\sigma_{emit}}{D}\gamma = \frac{\sqrt{\varepsilon_n \beta_{dipole}}}{D}\gamma^{\frac{1}{2}}$
- TDS resolution
  - Time resolution $\sigma_t = \frac{mc^3}{e}\frac{\sqrt{\varepsilon_n/\beta_{TDS}}}{\sin\Phi}\frac{\sqrt{\gamma}}{\omega_{TDS}V_{TDS}}$
  - Energy resolution $\sigma_{TDS} = \frac{e}{c}\sqrt{\varepsilon_n\beta_{TDS}}\frac{\omega_{TDS}V_{TDS}}{\sqrt{\gamma}}$
  - $\sigma_t\sigma_{TDS} = mc^2\frac{\varepsilon_n}{\sin\Phi}$

- Dipole resolution due to scr resolution

	SwissFEL	XFEL	PITZ	PITZ
Energy (MeV)	400-100	130	20	20
Scr (um)	33	28	100	33?
Dispersion (m)	1.5	1.2	0.9	0.9
Dipole (keV)	8.8-2.2	3.03	2.22	0.73

- TDS resolution (assume 90 deg phase advance)

	Charge (pC)	Emittance (um)	$\sigma_t\sigma_{TDS}$ (keV.ps)
SwissFEL	200	0.15-0.20	0.26-0.35
XFEL/PITZ	250	0.4-0.6	0.68-1

  - For DESY case, 0.1 ps resolution → 6.8-10 keV
  - Higher time resolution → worse energy resolution

- Energy chirp effect (linearizer off)
  - $\gamma \approx \gamma\cos\omega t \approx \gamma(1-\frac{(\omega t)^2}{2})$ → $\sigma_\gamma \approx \frac{\gamma}{\sqrt{180}}(\omega t_{slice})^2$

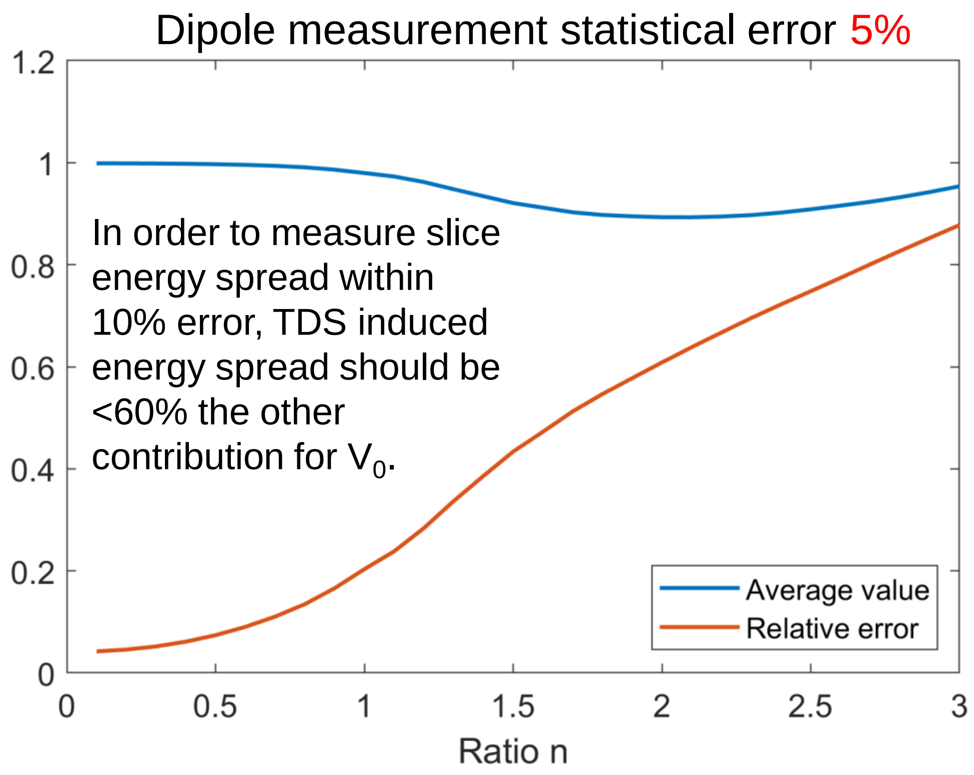
	SwissFEL	XFEL	PITZ
Energy (MeV)	400 – 100	130	20
Freq (GHz)	3	1.3	1.3
Slice full width (ps)	0.2	0.2	0.2
Energy spread (eV)	420-105	26	4

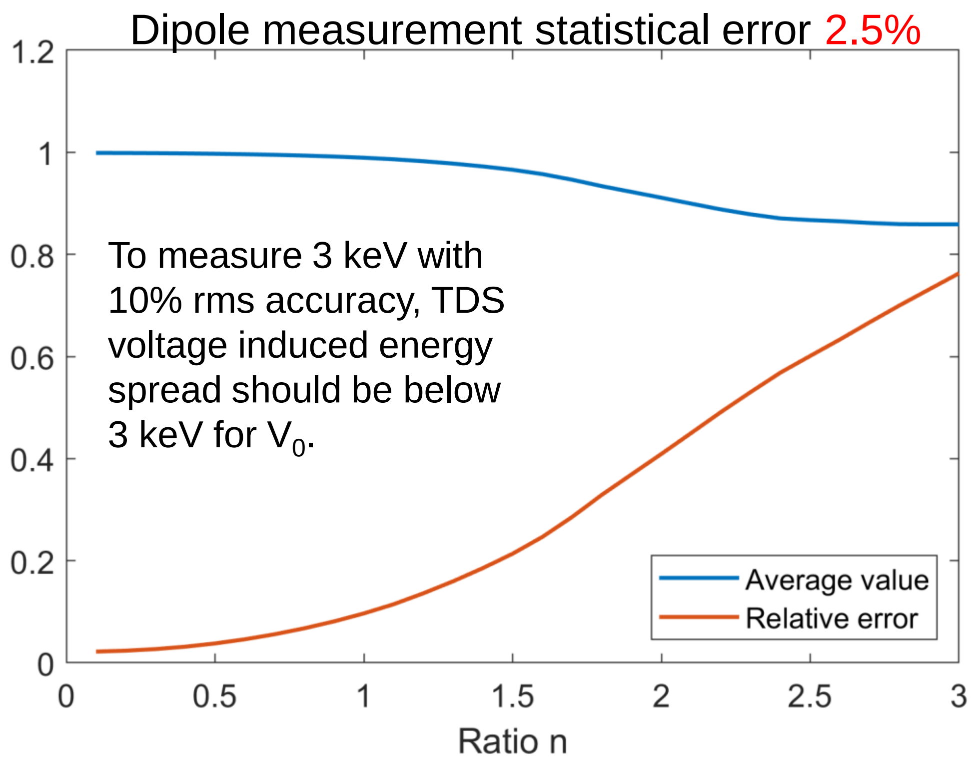
Slice energy spread measurement

TDS energy spread effect on measurement accuracy

$$\left(\frac{\sigma_M}{\sigma_0}\right)^2 = 1 + \left(n\frac{V_{TDS}}{V_0}\right)^2$$

- Assumptions
  - A TDS voltage scan with a range of 3, e.g. V_0, $1.5V_0$, $2V_0$, $2.5V_0$, $3V_0$
  - The dipole energy spread measurement rms error is 5% (2.5%)
  - V_0 induces an energy spread n times the contribution from (Screen + emit + real energy spread)

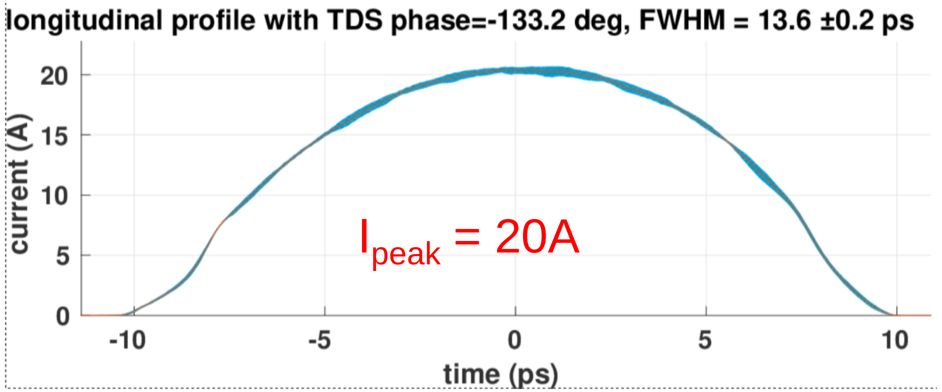


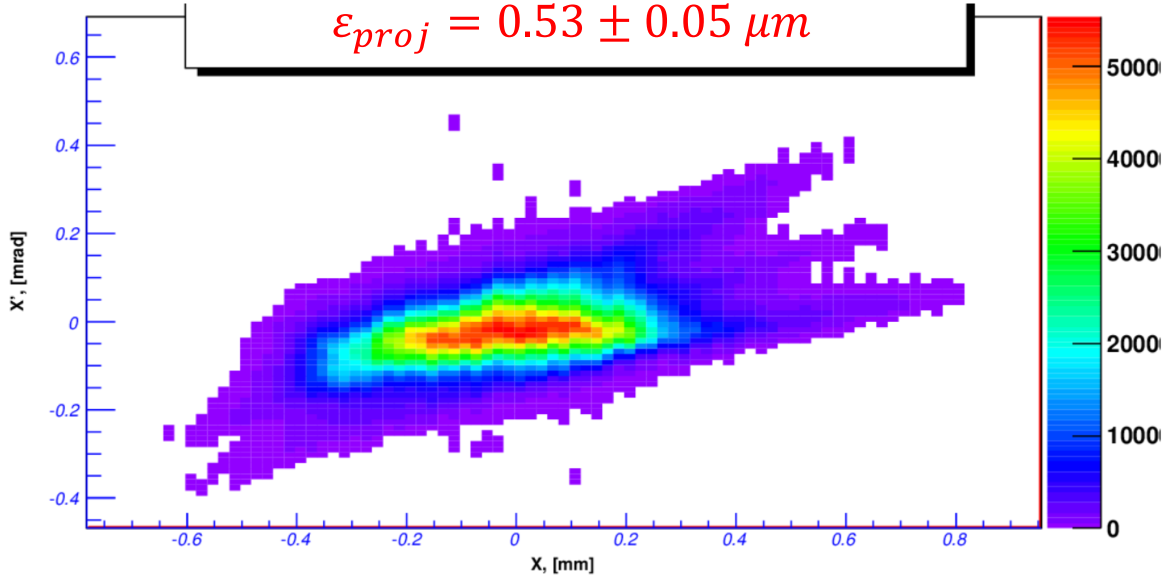


PITZ injector setup for the slice energy spread measurements

@XFEL injector working point

- Injector parameters
  - Charge 250 pC
  - MBI Laser,1 mm diameter, 7-8 ps FWHM Gaussian
  - Gun 4.2 exit, 6.3 MeV/c, max energy gain phase
  - Booster exit 19.6 MeV/c, max energy spread phase
    - For slice energy spread measurement, min energy spread phase
  - Solenoid 373 A, best emittance at booster exit
- Measurement locations
  - Emittance
    - 5.28 m from cathode, by slit scan
  - Temporal profile
    - 11 m from cathode, by TDS
  - Longitudinal phase space
    - 18.6 m from cathode, by TDS + dipole





Slice energy spread measurement at PITZ

Use a slit mask to measure betatron contribution and screen resolution

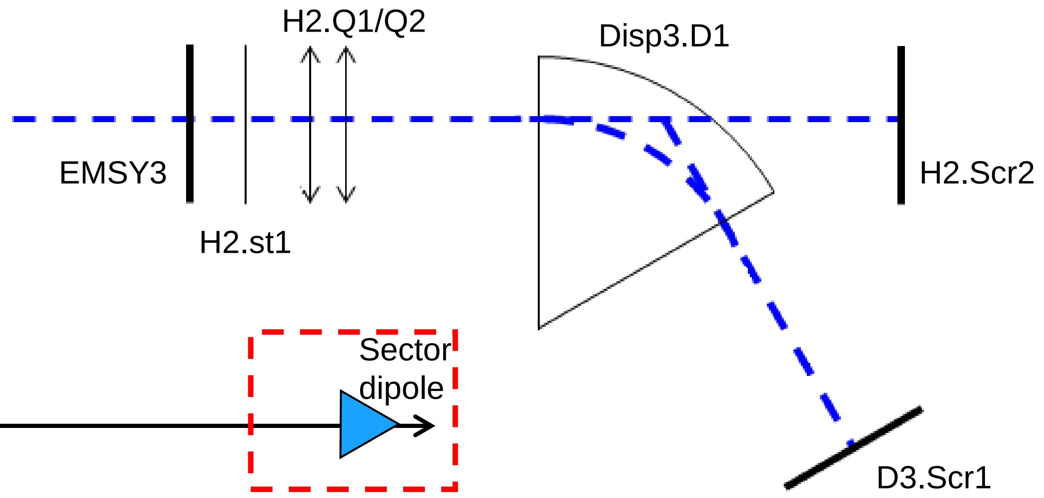
- PITZ beam (~20 MeV) @ XFEL working point (250 pC, 0.4-0.6 mm.mrad, 20 A) is space charge dominated.
- Both energy scan (PSI) and dispersion scan (XFEL) requires a constant central slice beta function at dipole screen, not easy for PITZ case.

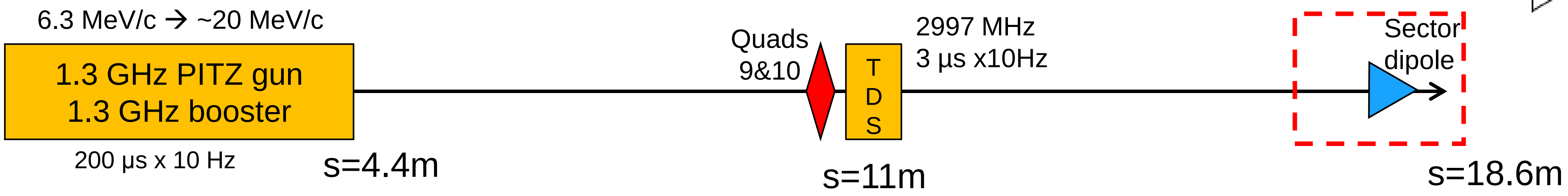
$$\sigma_M^2 = \sigma_{scr}^2 + \sigma_{emit}^2 + \left(D\frac{\sigma_{E0}}{E}\right)^2 + \left(D\frac{\sigma_{TDS}}{E}\right)^2$$

- Instead, we can use a slit mask to mitigate space charge forces, assuming transverse distribution is dominated by emittance, i.e. no filtering of energy.

- PITZ TDS kick in y; Disp3.D1, 60 degree sector dipole, dispersion @D3.scr1, 0.9 m, bend in x
- EMSY3 station has horizontal and vertical slits
  - X axis slit, 50 um width, 10 mm height
  - Y axis slit, 10 um height, 10 mm width
  - A steerer is 10 cm downstream the slit

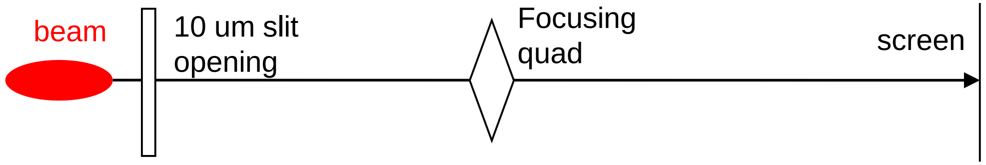
$$\sigma_{emit} = R_{12X} * \sigma_{x'}$$



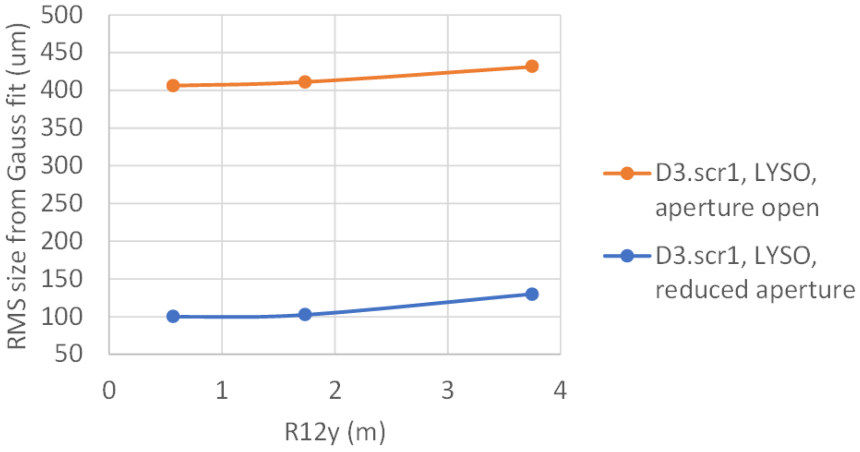


Screen resolution measurement with a slit

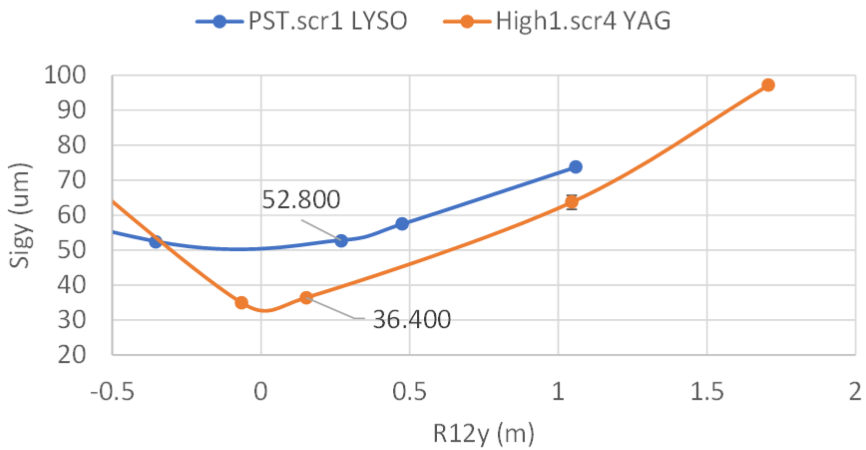
- Screen resolution measurement setup

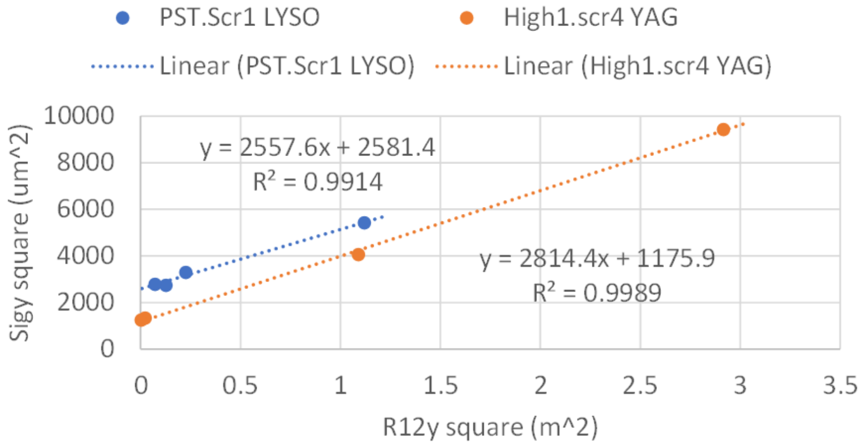


  - $\sigma_y^2 = \sigma_{scr}^2 + R_{12}^2 * \sigma_{y'}^2$, fit screen resolution
- Disp3.scr1 resolution
  - 400 um rms → 100 um rms with reduced lens aperture
  - ~70 um rms with very small lens aperture, but signal extremely weak for measurements



- PST.scr1 LYSO screen: 51 um rms
- High1.scr4 YAG screen: 34 um rms

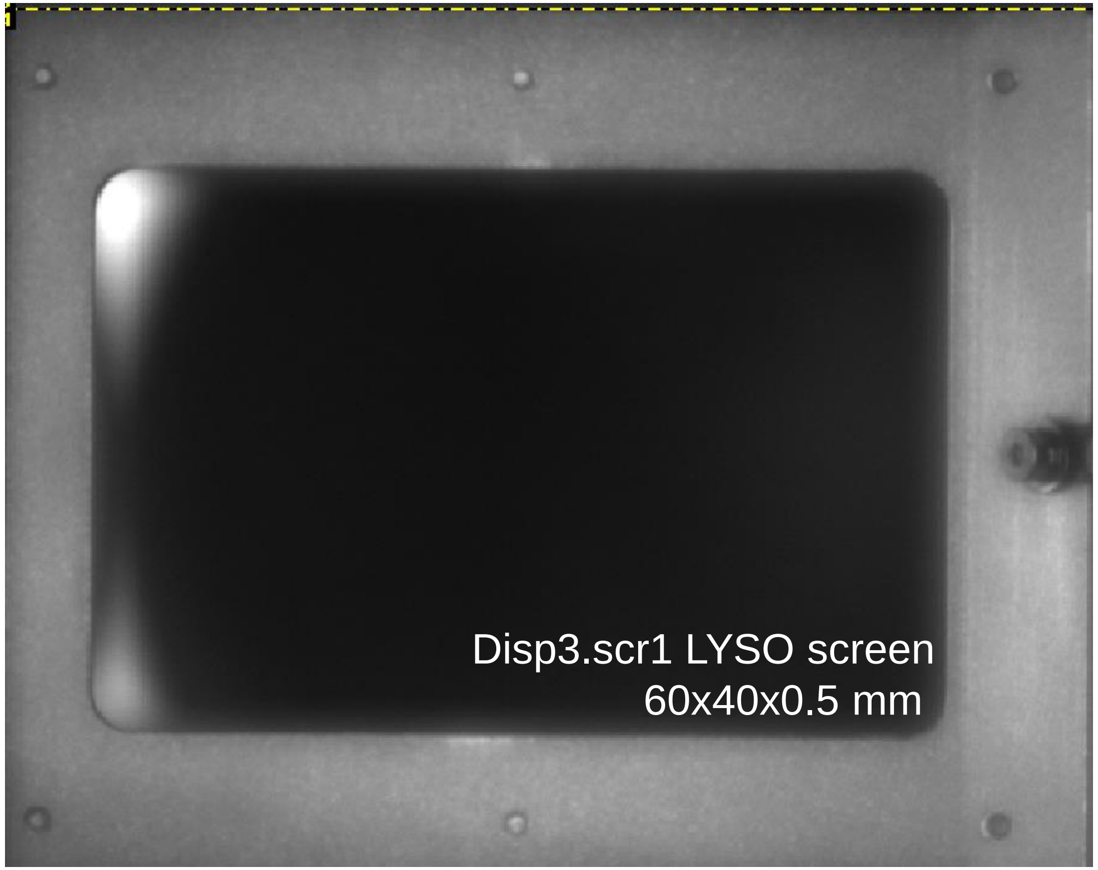




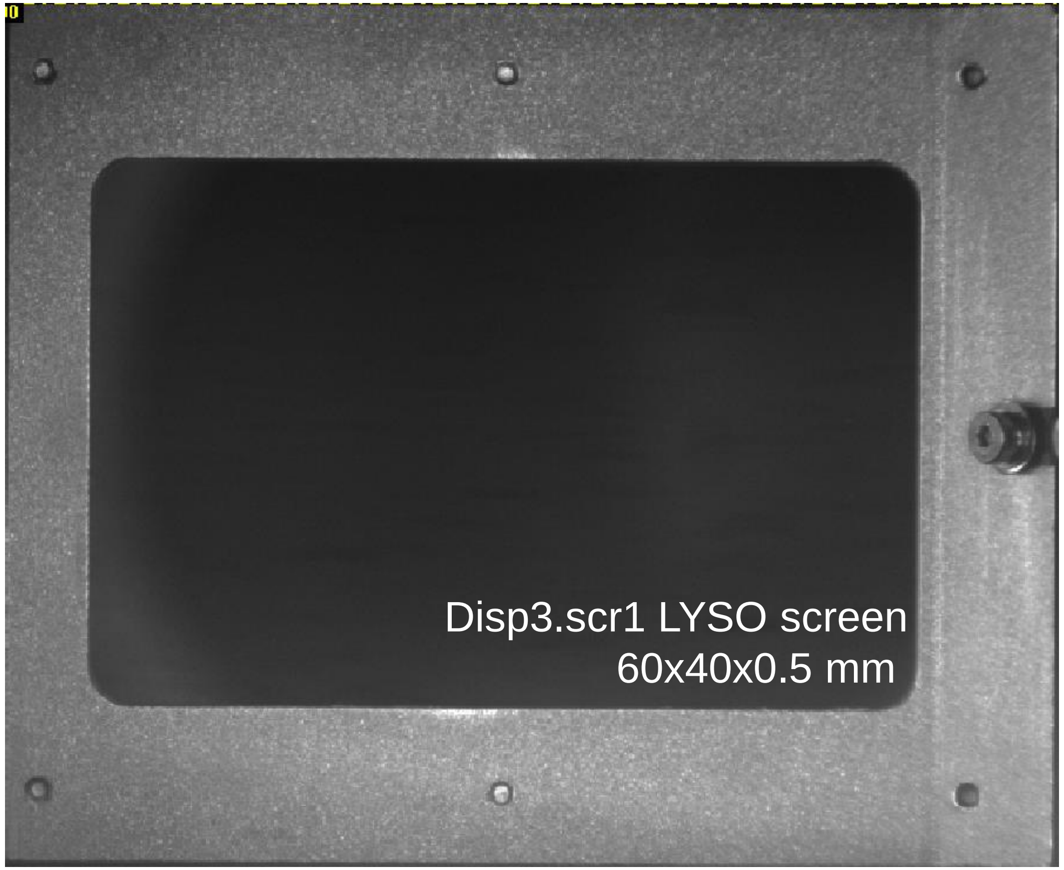
Optical aberration

Disp3.scr1

400 um rms resolution with fully open lens aperture



100 um rms resolution with reduced lens aperture



To further improve Disp3.scr1 resolution, camera imaging setup has to be changed, maybe LYSO screen thickness should reduce too?

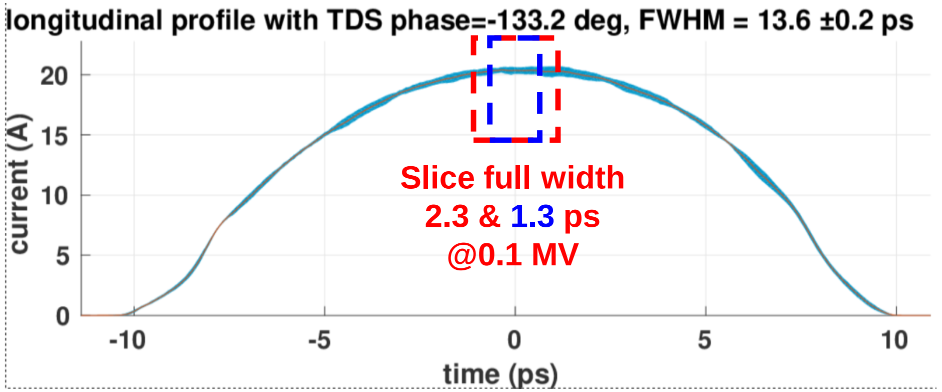
TDS voltage scan

Vs beam focusing before slit

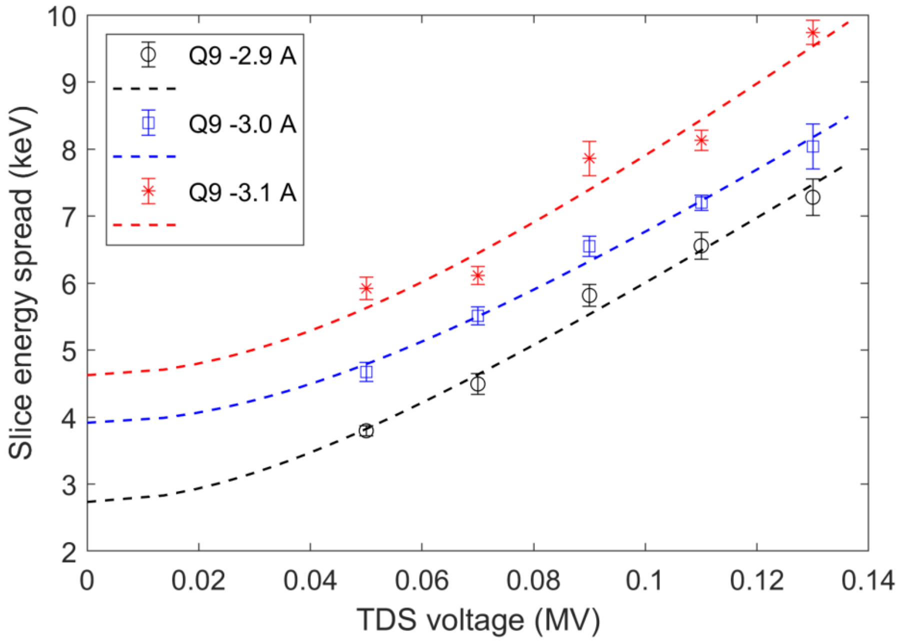
- Cs2Te cathode (5 nm Te)

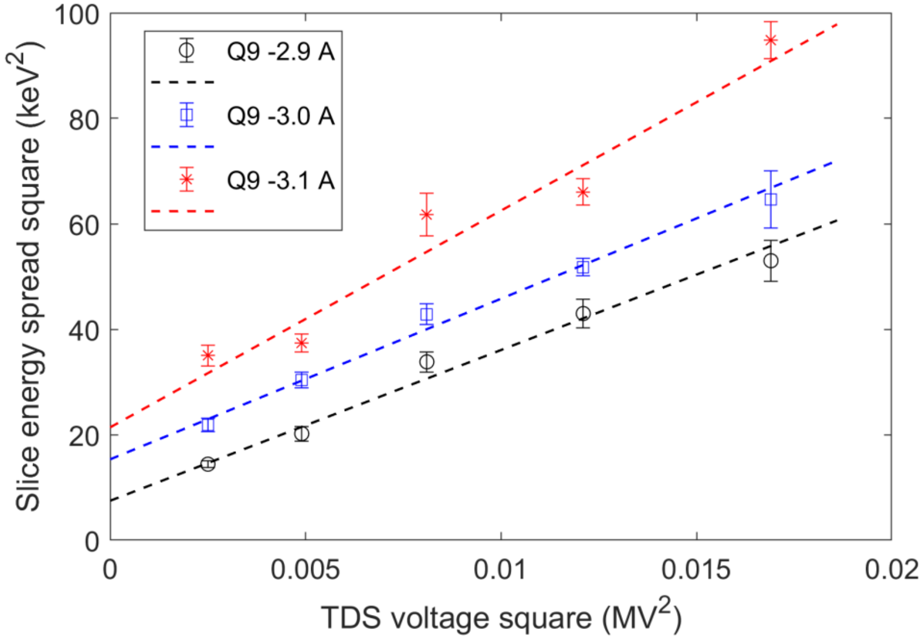
H1.Q10 (A)	w/o TDS dE* (keV)	emittance contribution** (keV)	~110 um screen resolution (keV)	rms time resolution @0.05 MV (ps)
-2.9	2.7 ± 0.3	0.75	2.4	0.54
-3.0	3.9 ± 0.2	0.83	2.4	1.46
-3.1	4.6 ± 0.5	0.90	2.4	2.2

* Screen resolution + emittance + real slice energy spread
** dominated by LYSO screen resolution, expected to be ~50% lower



Slice energy spread results are very similar using either 2.3 ps (15 pixel line) or 1.3 ps (9 pixel line) slice width.



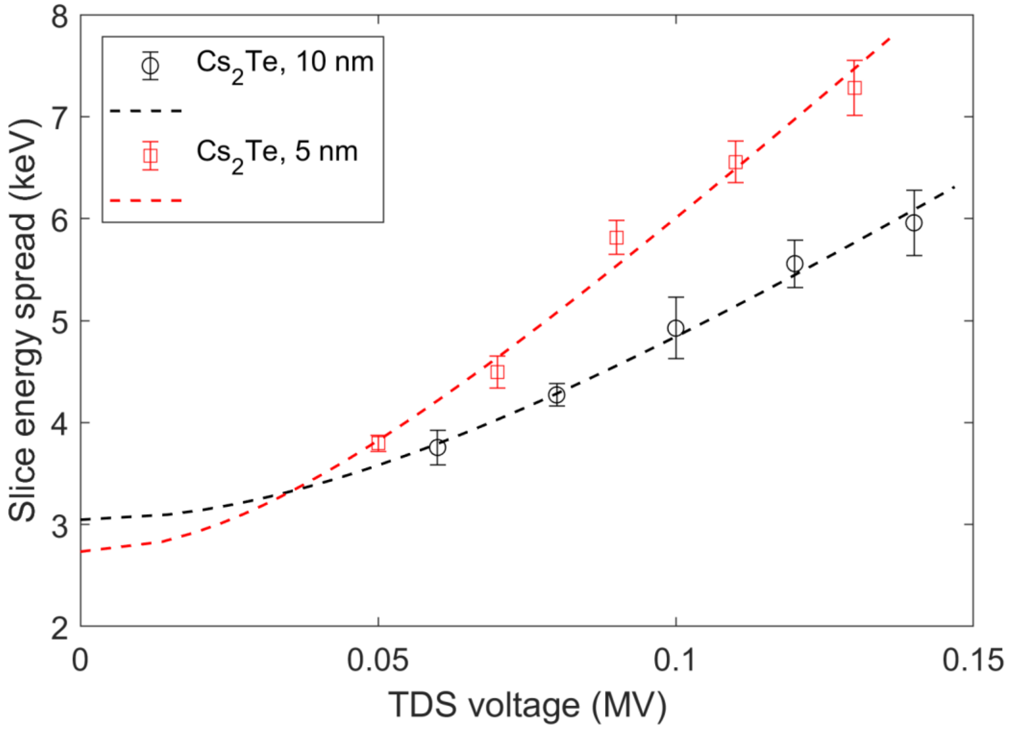


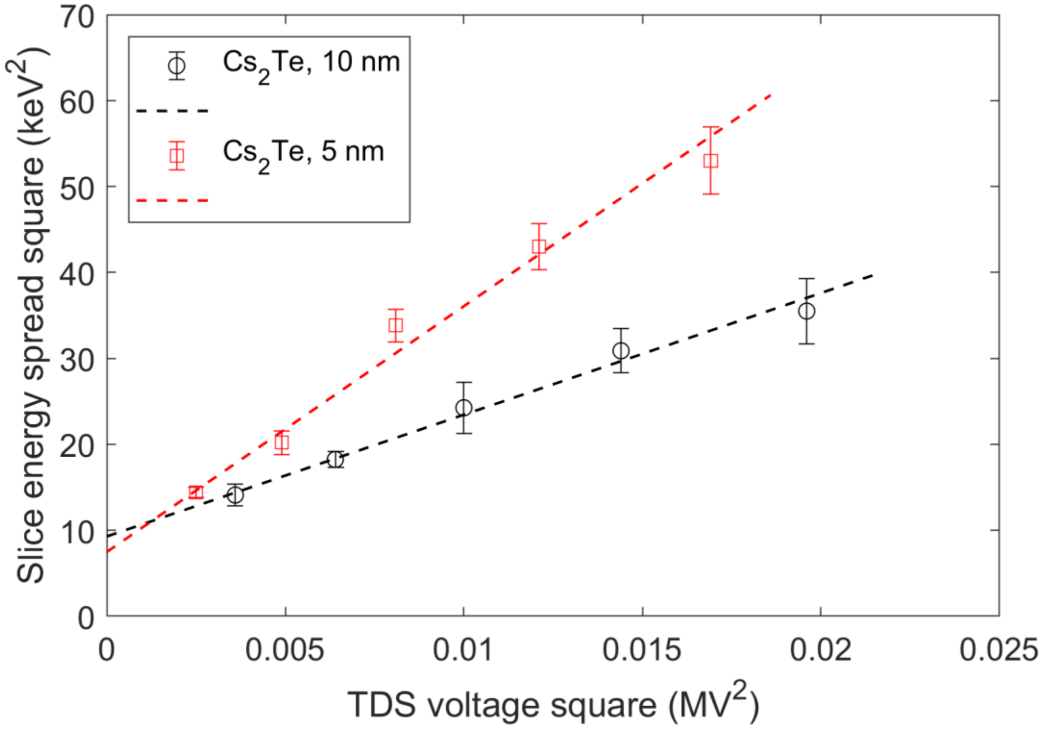
TDS voltage scan

Cs2Te (5 nm) vs Cs2Te (10 nm)

- Cs2Te cathode (Q10 -2.9 A)

Cs2Te	w/o TDS dE (keV)	emit contribution (keV)	screen resolution (keV)	time resolution @0.05 MV (ps)	TDS δE @0.05 MV (keV)	Ratio n
5 nm	2.7 ± 0.3	0.75	2.4	0.54	2.7	1
10 nm	3.0 ± 0.1	0.92	2.4	0.46	1.8	0.6





Summary & outlook

- Summary
  - Screen resolution ~110 um rms @D3.Scr1, ~2.4 keV, dominating final results
  - Emittance contribution is below 1 keV with the slit cutting down the x emittance
  - Best TDS streaking setup has a proper time resolution and small induced energy spread.
  - Very low energy spread (1-1.5 keV rms, below screen resolution) not understood
  - Energy spread variation from beam focusing before slit not understood
    - Improper phase advance after touching Q10 current by 0.1 A?
    - Time resolution degradation (2.2 ps rms @0.05 MV, 4.4 ps full width) induces ~2 keV contribution from 2^{nd} order energy chirp
    - Booster and TDS phase jitter effect?
    - Slit mask filtering energy spread? How?
- Next
  - Improve dispersion screen camera setup for both resolution and efficiency, and maybe reduce screen thickness
  - Improve TDS streaking setups to maximize both phase advance and charge through slit
  - Test slits before TDS
  - Try other charges, e.g. 100 pC, 500 pC
  - More simulations