Considerations for low energy slice energy spread measurements

Chris Richard

HELMHOLTZ

Slice energy spread (SES) measurements

SES measurements are crucial for understanding FEL performance

- FEL brightness is dependent on the slice energy spread
- SES is typically ~keV, making it challenging to measure
  - Need to properly account for systematic errors
- High energy machines → dispersion scan
  - Can ensure the rest of the parameters are constant

$$\sigma_{\text{meas}}^2 = \left(\sigma_{\text{E}} \frac{D}{E}\right)^2 + \sigma_{\text{scr}}^2 + \sigma_{\perp}^2 + \left(\sigma_{\text{E,TDS}} \frac{D}{E}\right)^2$$

SES | Imaging system resolution | Non-dispersive size | Energy spread from TDS

	SDUV	FERMI	SwissFEL	Eu-XFEL	Unit
Q	100	600	200	250	pC
E_k	136	1320	100	130	MeV
I	12	800	20	20	A
σ_E	1.2	40	15	5.9	keV
I/σ_E	10	20	1.3	3.4	A/keV
Method	Undulator radiation		Dispersion		…
Reference	[33]	[40]	[31]	[32]	…

Photo Injector Test Facility at DESY Zeuthen (PITZ)

20 MeV photoinjector with flexible beam parameters and diagnostics

Primary goals of PITZ

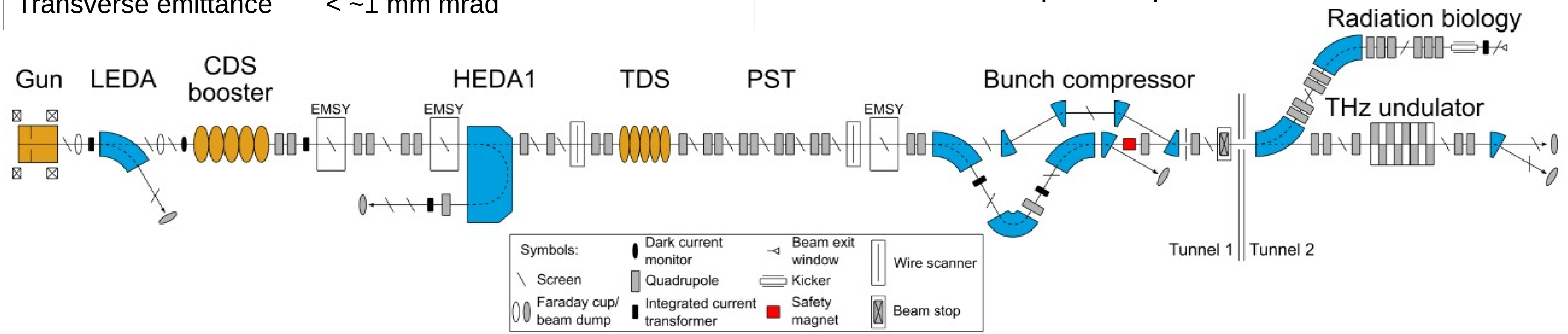
- Commission and characterize electron sources for FLASH and European XFEL
- General accelerator R&D

Typical beam parameters

Charge	10 pC – 3 nC (250 pc nominal)
Energy	17-25 MeV (20 MeV nominal)
Transverse emittance	< ~1 mm mrad

Overview of available diagnostics

- Charge - ICT and Faraday cups
- Momentum - low and high energy dispersive arms
- Bunch size – scintillating screens
- Bunch length – TDS
- Longitudinal phase space – TDS, tomography
- Transverse phase space – Slit-screen scans



SES measurements at PITZ

Can use existing diagnostics for SES measurements

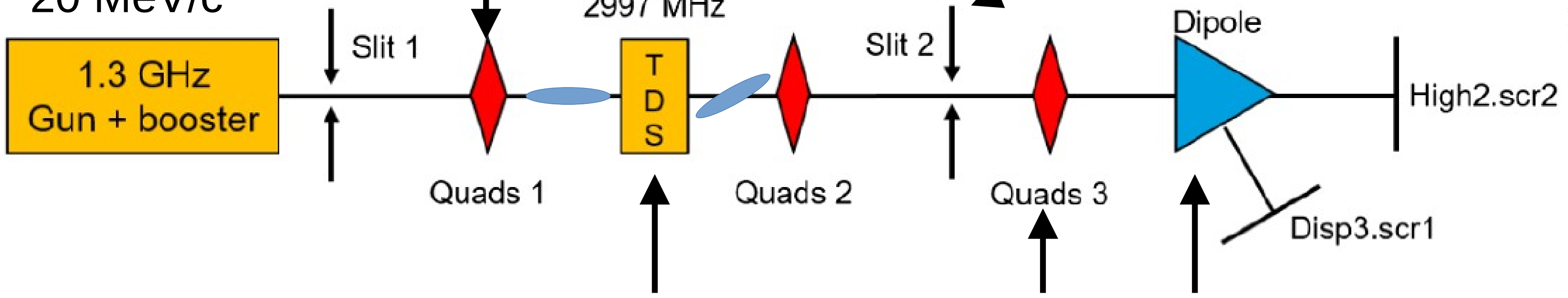
$$\sigma_{\text{meas}}^2 = \left(\sigma_{\text{E}} \frac{D}{E}\right)^2 + \sigma_{\text{PSF}}^2 + \sigma_{\perp}^2 + \left(\sigma_{\text{E,TDS}} \frac{D}{E}\right)^2$$

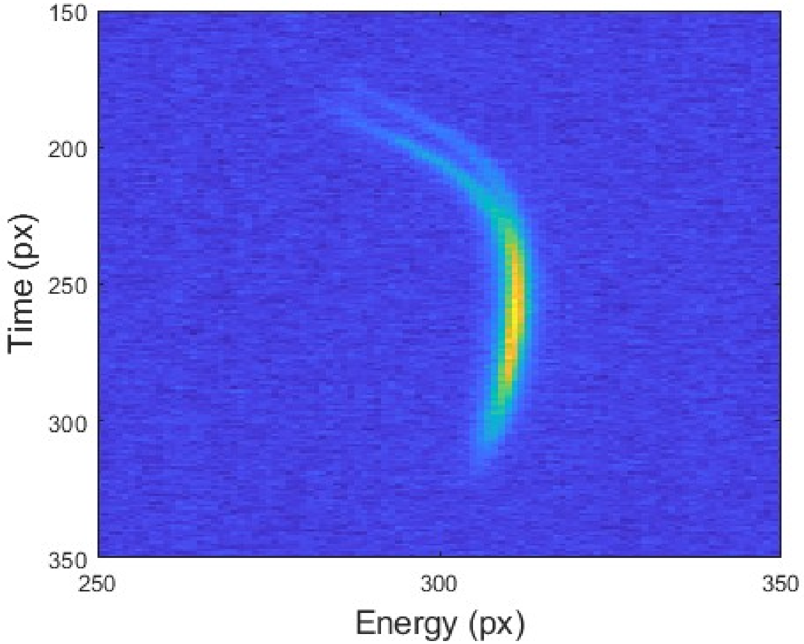
$$\sigma_{\text{E},\perp} = \sigma_{\perp} \frac{E}{D} \qquad \sigma_{\text{E,PSF}} = \sigma_{\text{PSF}} \frac{E}{D}$$

	Energy (MeV)	Dispersion (m)	E/D (keV/mm)
PITZ	20	0.9	22
European XFEL	130	1.2	108

Low energy SES measurements

- Screen and transverse size contributions are proportional to energy → better resolution at low energies
- Dispersion scans are challenging
  - Cannot keep constant beam size due to space charge
- Requires measuring each term separately





SES measurement resolution – Screen contribution

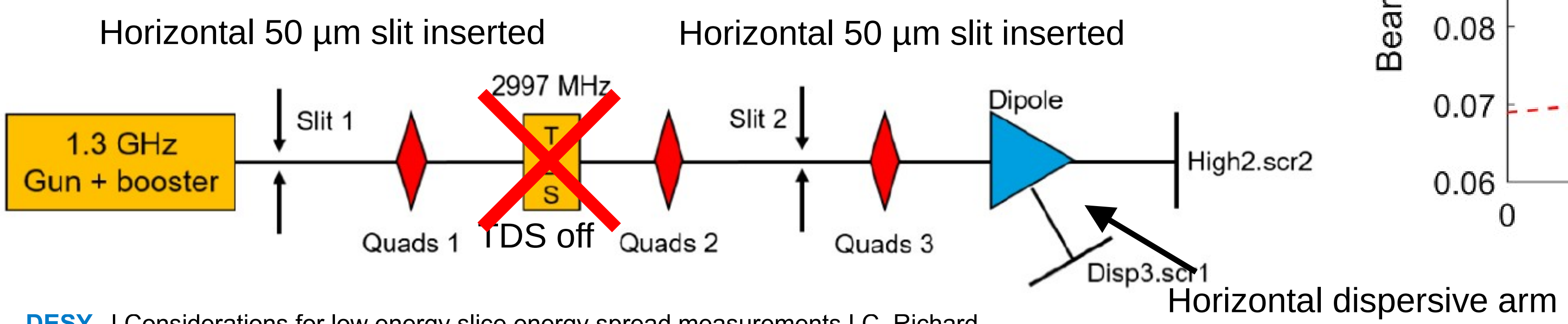
Measured distribution is convolution of true distribution with the camera resolution

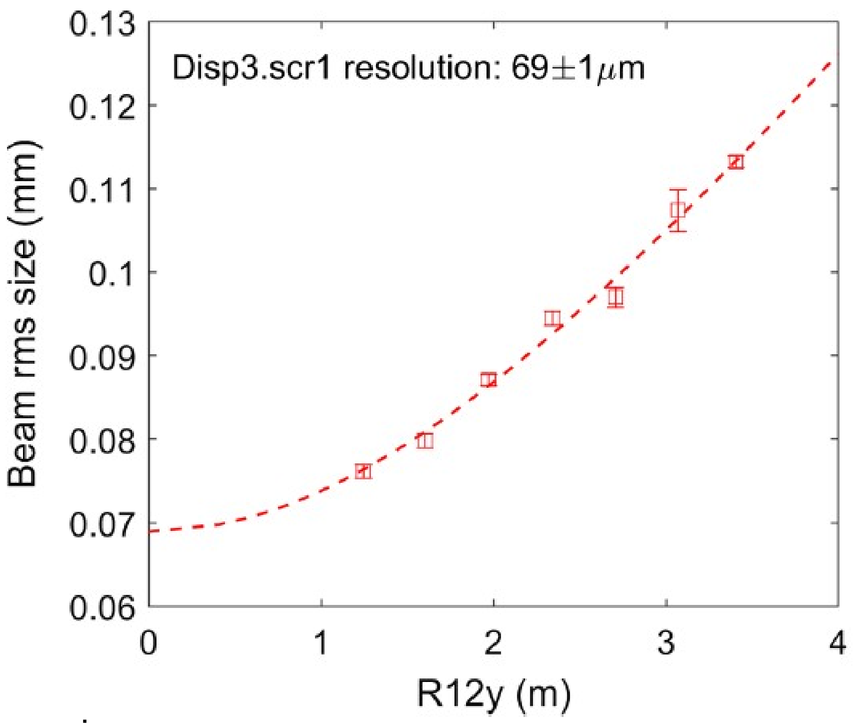
Measuring the camera resolution

- Insert horizontal slit at Slit2 to reduce vertical emittance
- Scan Quads3 to vary R12y through the dispersive arm
  - R12 measured by scanning the beam position
- Fit beam size vs R12y to get resolution
  - Measured: 69 µm = 1.5 keV
- Can improve resolution by reducing camera aperture at the cost of SNR

$$\sigma^2_{\mathrm{meas}} = \sigma^2_{\mathrm{true}} + \sigma^2_{\mathrm{scr}}$$

$$\sigma^2_y \approx \sigma^2_{\mathrm{scr}} + \left(R_{12y} \cdot \sigma_{y',0}\right)^2$$





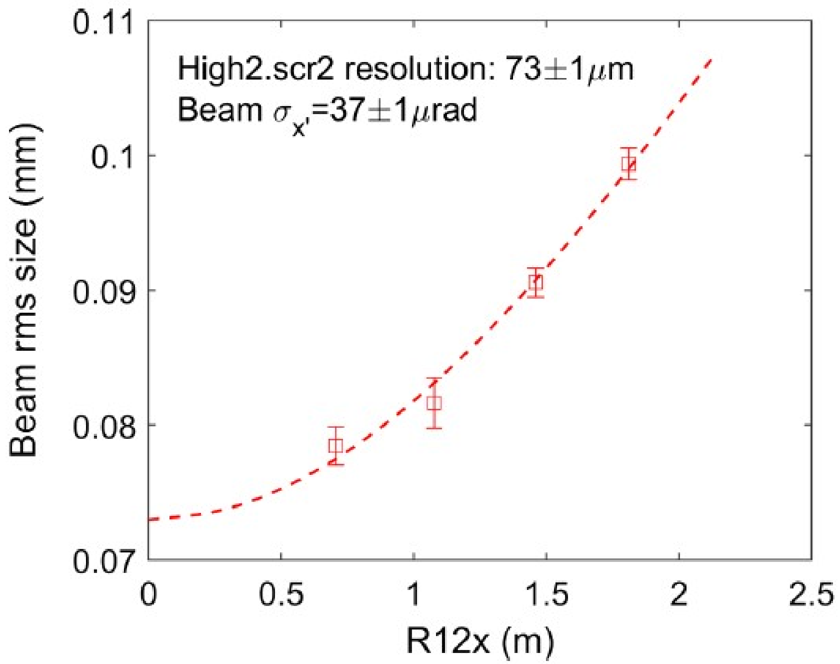
SES measurement resolution – Emittance contribution

Measured beam size in the dispersive arm is combination of

Measuring the emittance contribution

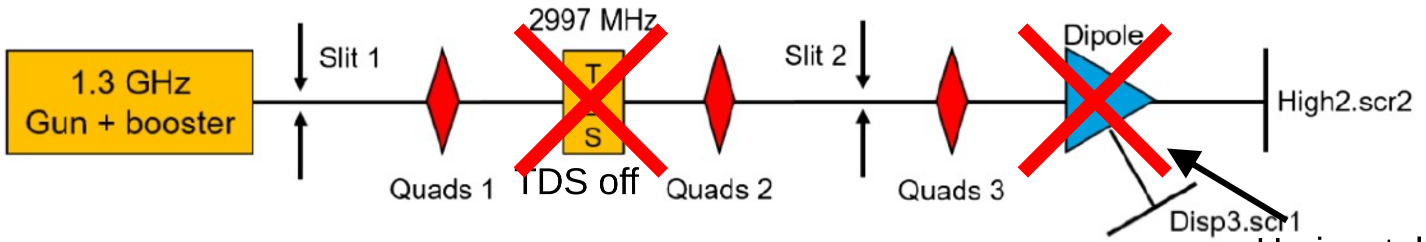
$$\sigma_y^2 \approx \sigma_{scr}^2 + (R_{12y} \cdot \sigma_{y',0})^2$$

- Insert vertical slit at Slit 2 to reduce horizontal emittance
- Turn off dipole
- Scan Quads3 to vary R12x through the straight section
  - Fit to get rms angle at the slit
- Turn on dipole. Measure R12x through dispersive arm
- Measured: 30 μm = 0.65 keV



Horizontal 50 μm slit inserted

Vertical 50 μm slit inserted



Horizontal dispersive arm

SES measurement resolution – TDS contribution

TDS fields introduce additional energy spread

$$\sigma_{\rm meas}^2 = \left(\sigma_{\rm E}\frac{D}{E}\right)^2 + \sigma_{\rm scr}^2 + \sigma_{\perp}^2 + \left(\sigma_{\rm E,TDS}\frac{D}{E}\right)^2$$

Measuring the non-TDS contribution

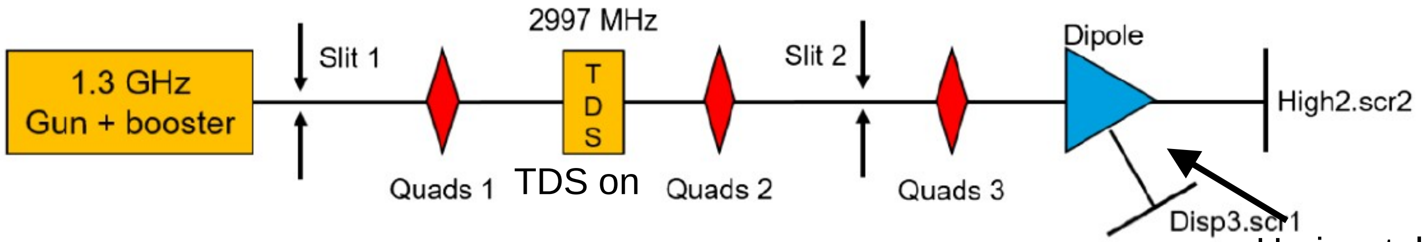
- Slit1 – horizontal slit inserted → reduce ß at TDS
- Slit2 – vertical slit inserted → reduce ε in dipersive arm
- Scan TDS voltage and measure SES
- Fit SES vs TDS voltage to remove TDS contribution
  - Measured: 107 µm = 2.32 keV

$$\sigma_{\rm E,TDS} \propto V_{\rm TDS}\sigma_{\perp,\rm TDS}$$

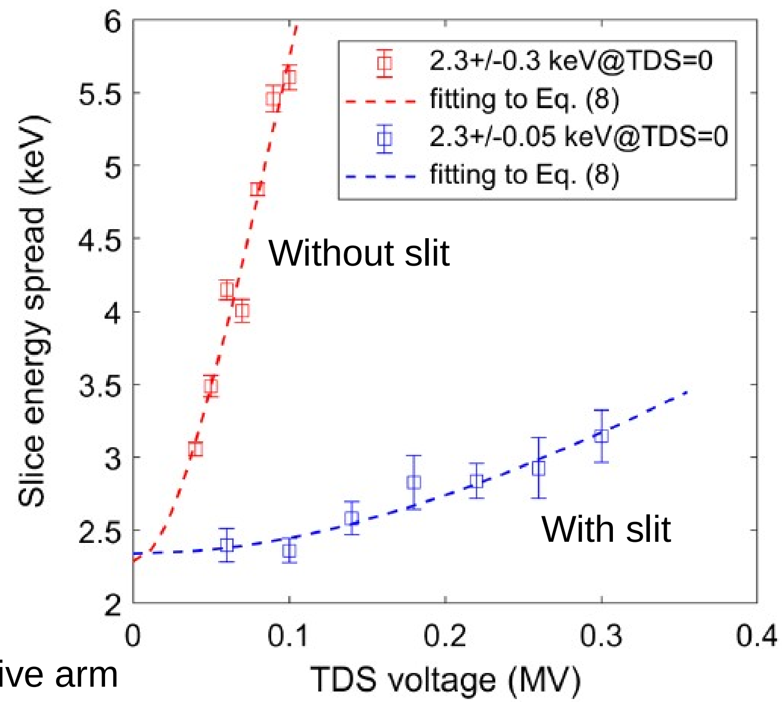
$$\sigma_{\rm meas}^2 = \sigma_0^2 + aV_{\rm TDS}^2 \quad \text{(Eq. 8)}$$

Horizontal 50 µm slit inserted

Vertical 50 µm slit inserted



Horizontal dispersive arm



SES measurement resolution – TDS contribution

TDS fields introduce additional energy spread

$$\sigma^2_{\mathrm{meas}} = \left(\sigma_{\mathrm{E}} \frac{D}{E}\right)^2 + \sigma^2_{\mathrm{scr}} + \sigma^2_{\perp} + \left(\sigma_{\mathrm{E,TDS}} \frac{D}{E}\right)^2$$

Measuring the non-TDS contribution

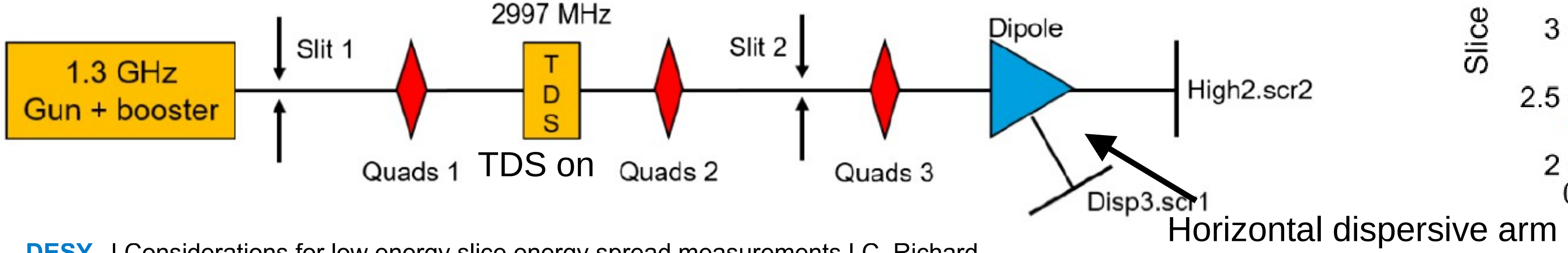
- Slit1 – horizontal slit inserted → reduce ß at TDS
- Slit2 – vertical slit inserted → reduce ε in dipersive arm
- Scan TDS voltag
- Fit SES vs TDS v
  - Measured: 1

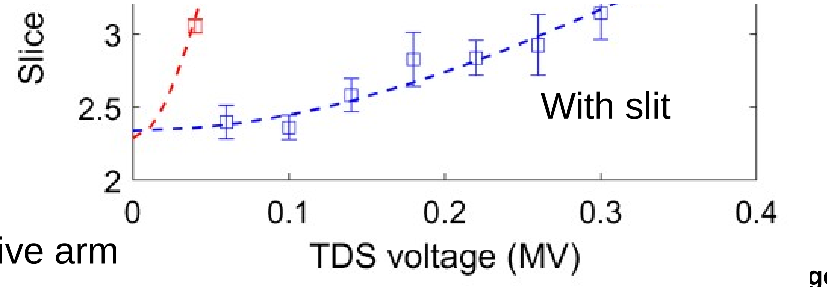
$$\sigma_{\mathrm{E,TDS}} \propto V_{\mathrm{TDS}} \sigma_{\perp,\mathrm{TDS}}$$

$$\sigma^2_{\mathrm{meas}} = \sigma^2_0 + a V^2_{\mathrm{TDS}}$$

Non-TDS contribution	Screen resolution	Emittance resolution	Real slice energy spread	Units
107 ± 2	69 ± 1	30 ± 1	76 ± 2	μm
2.32 ± 0.05	1.50 ± 0.02	0.65 ± 0.02	1.65 ± 0.06	keV

Horizontal 50 µm slit ir

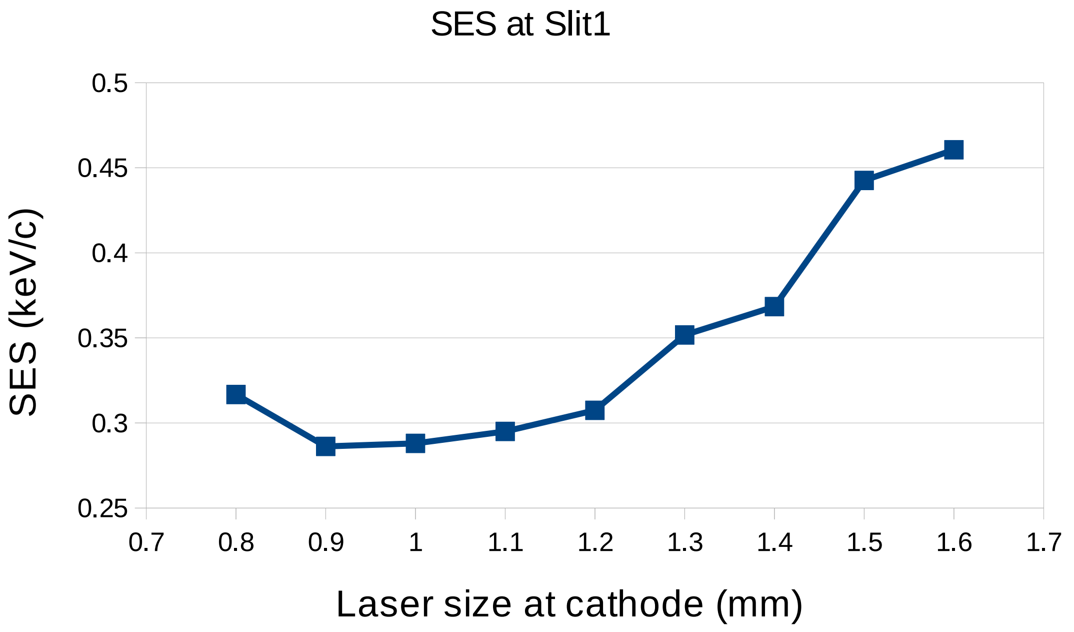


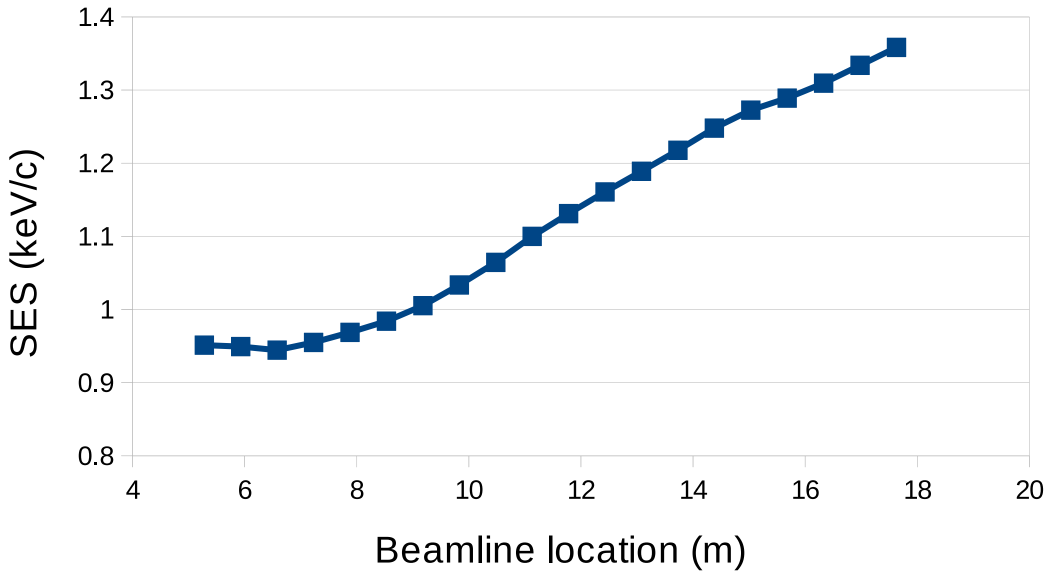


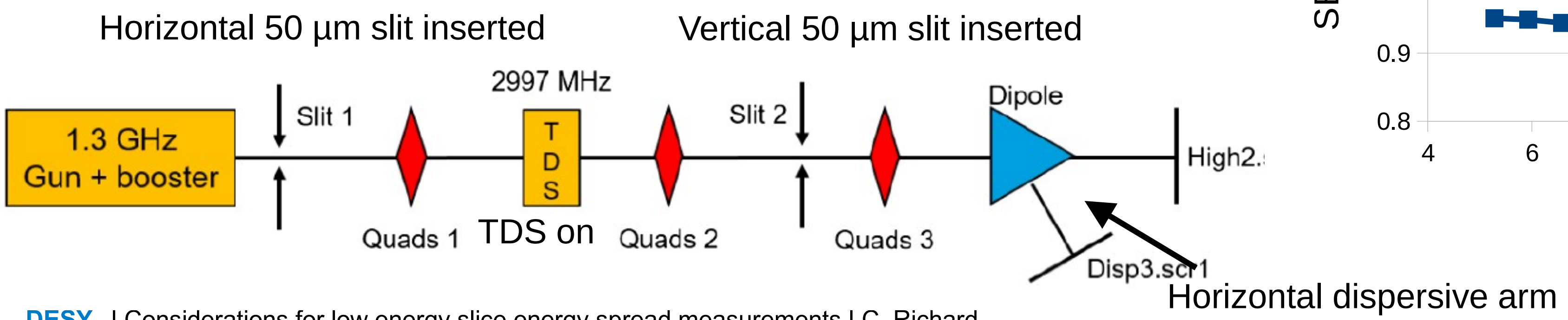
Space charge effects

Space charge plays a significant role in SES increase along the beamline

- Space charge plays key role in development of SES
  - Origin of measured SES goes back to the laser size on the cathode
- Simulations show SES increase during transport in measurement section
  - ~30% increase in SES from Slit1 to the measurement screen for 250 pC
- Insert slit1 to reduce effect, also improve TDS resolution



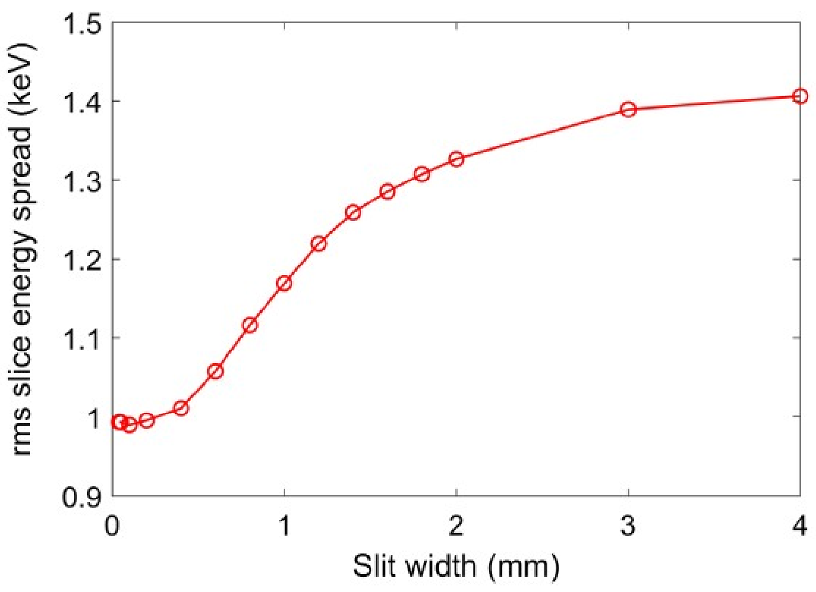


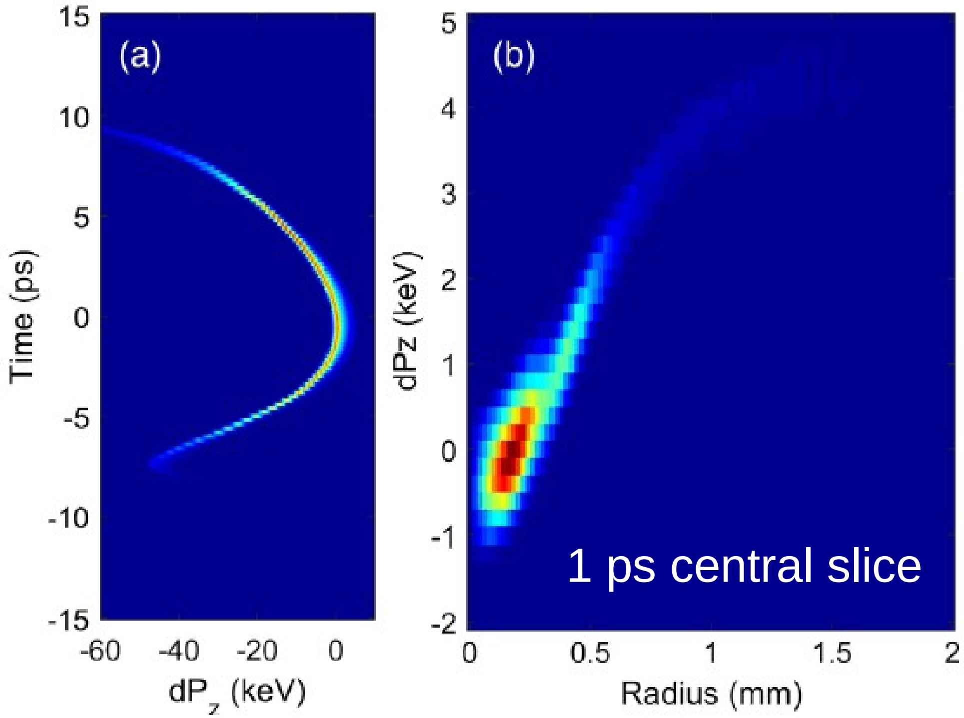


Transverse distribution dependence

Insertion of slits changes the measured SES

- The energy distribution can be dependent on the transverse distribution
  - → Inserting a slit changes the measured energy spread
- Can see ~40% change in SES in simulations when a 50 μm slit is inserted





Beam stability

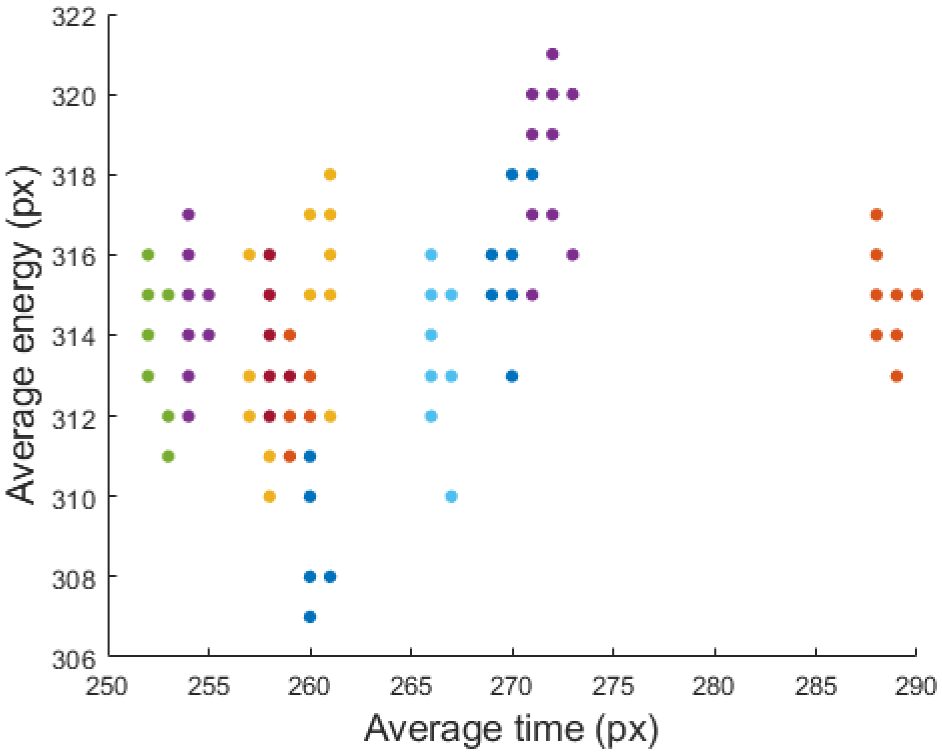
Even small jitter can causes problems

- Cannot average multiple images due to shot to shot beam jitter/drift
- Time jitter: ~50 px shift over TDS scan
  - Need care for where the central slice is defined
- Energy jitter: ~1-2 px rms = 1.4-2.8 keV rms
  - Energy jitter can be on the same order as the expected SES
  - Challenging to resolve transverse dependence due to this jitter

Non-TDS contribution	Screen resolution	Emittance resolution	Real slice energy spread	Units
107 ± 2	69 ± 1	30 ± 1	76 ± 2	μm
2.32 ± 0.05	1.50 ± 0.02	0.65 ± 0.02	1.65 ± 0.06	keV

E=20 MeV, D = 0.9m
Pixel size: 62.8 µm = 1.36 keV

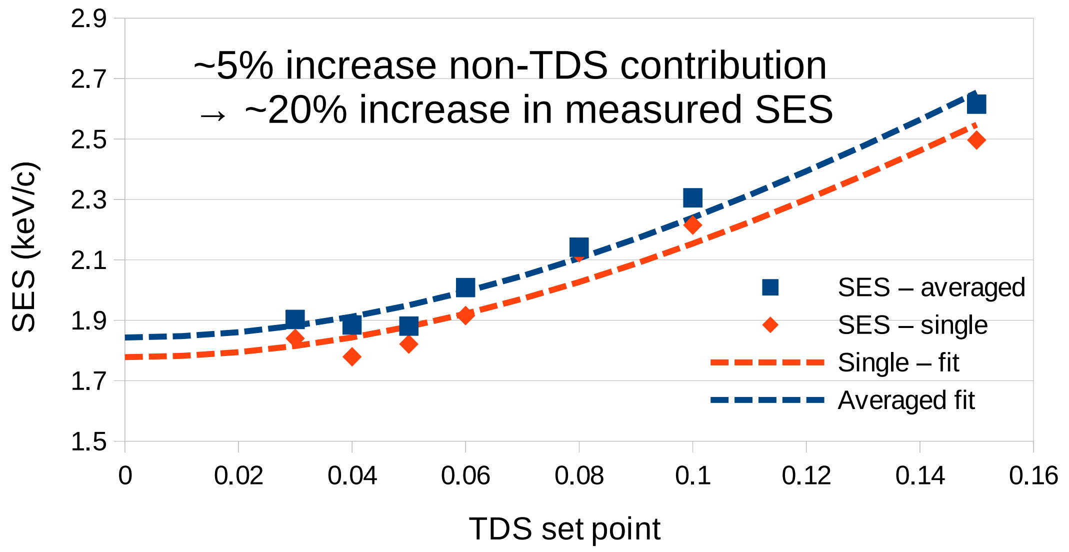
Beam centroid jitter

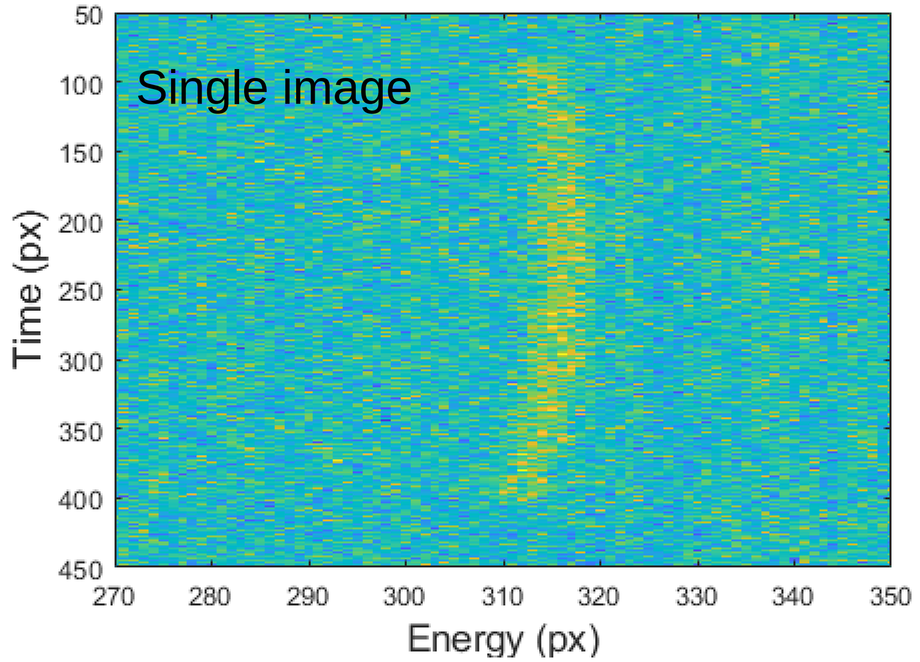


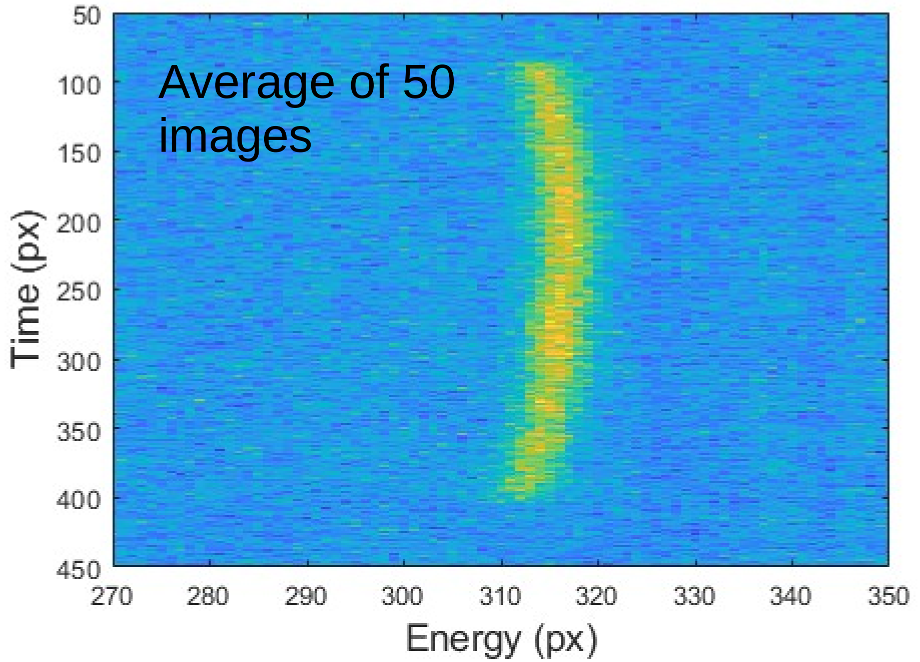
Signal to noise ratio

Low SNR makes SES calculation challenging

- 250 pC → 10 pC at screen due to slits
- Limited bunches per train in TDS due to klystron limitation
  - Single shot brightness is limited
- Can't average many pulses due to jitter increasing the measured size
  - SES results are sensitive to small changes because it is close to the resolution limit







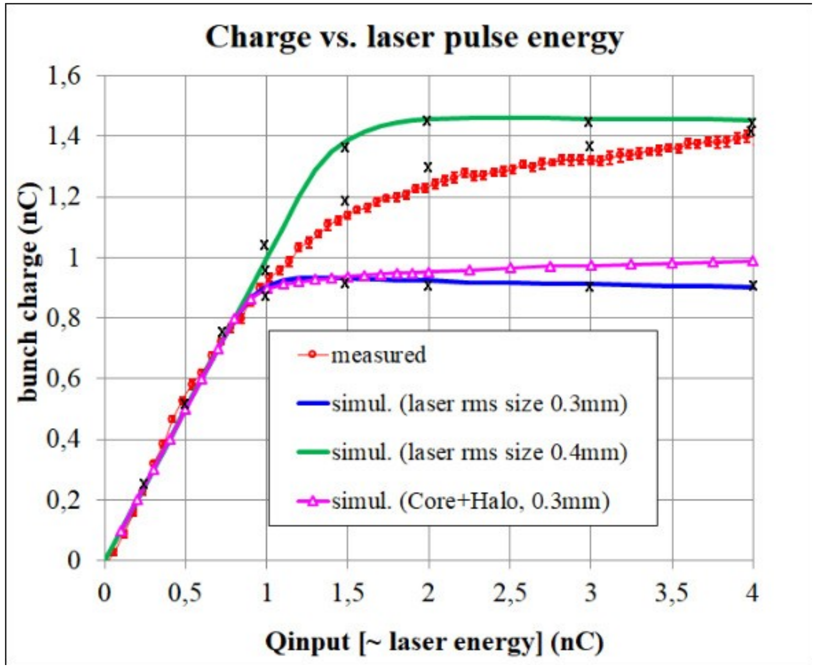
Possible causes of discrepancy with simulations

Simulations cannot properly replicate the emission process

- Measured SES: 1.65 keV
- Simulated SES: 0.75 keV

Possible causes of discrepancy

- Insufficient model of emission in ASTRA
- Intrabeam scattering
- Sensitivity to gun and booster – needs investigation
- Resolution limits of measurement



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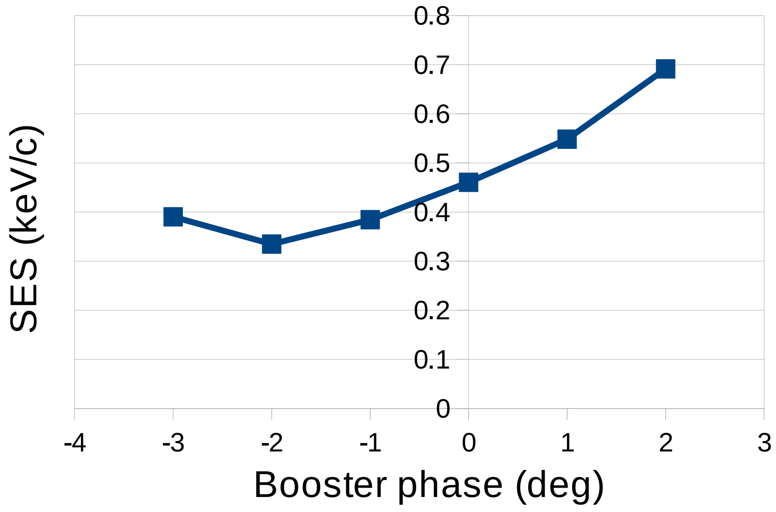
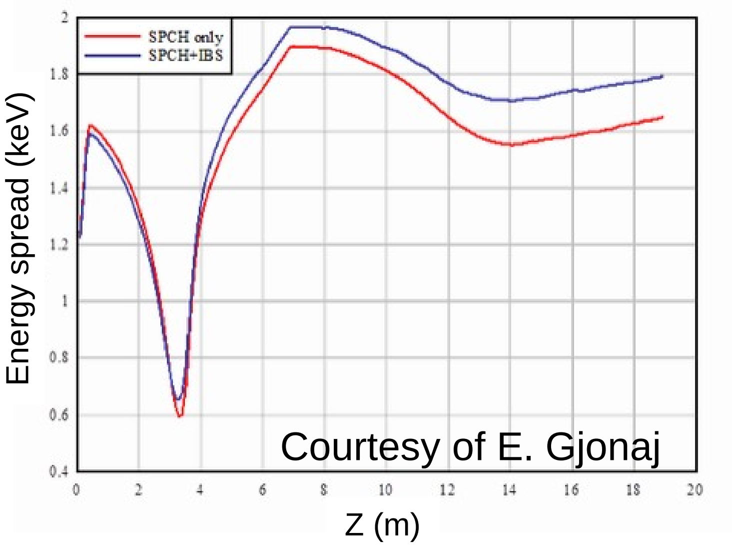


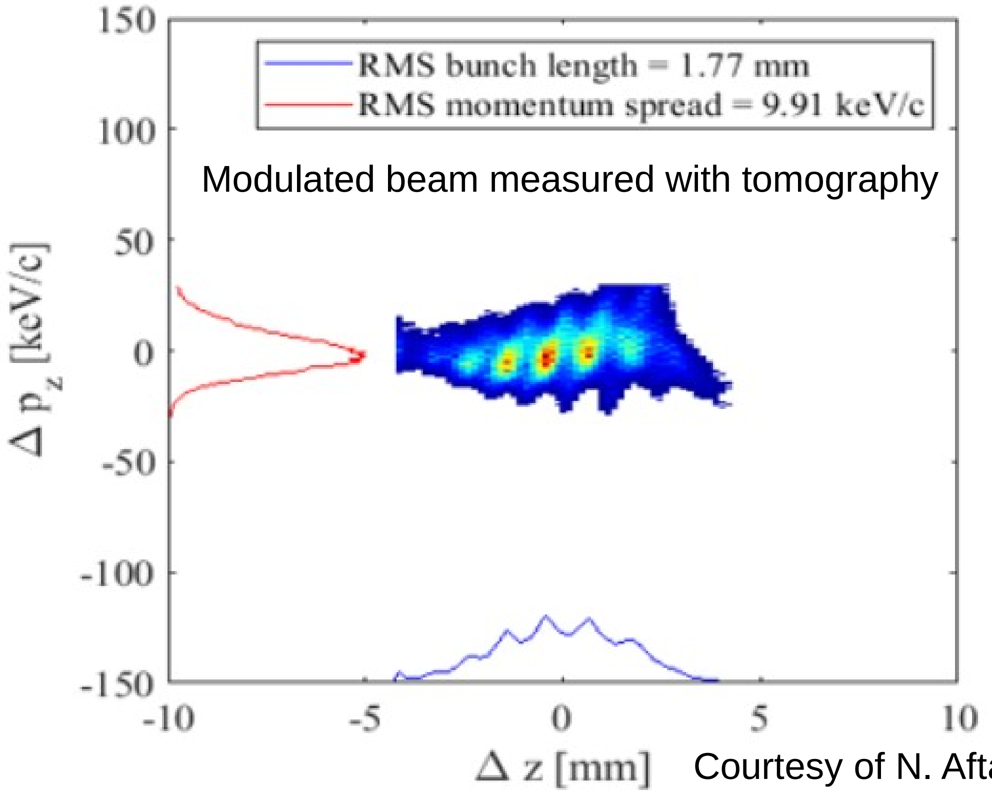


Summary and outlook

Plans for further investigations and improvements to the setup

Non-TDS contribution	Screen resolution	Emittance resolution	Real slice energy spread	Units
107 ± 2	69 ± 1	30 ± 1	76 ± 2	μm
2.32 ± 0.05	1.50 ± 0.02	0.65 ± 0.02	1.65 ± 0.06	keV

- We can measure SES at PITZ
  - Low energy machine → can get better resolution
- Care is needed to minimize errors
  - Insert slits to reduce effects of space charge, emittance, and TDS
  - But at the cost of SNR and not measuring the full beam
- Work on improving measurements
  - New laser → higher rep rate → higher SNR, better stability
  - Remote camera aperture control → optimize resolution
  - New tomography method being developed
- Plans for further investigations
  - Variations with gun and booster parameters
  - Variations with bunch charge



Courtesy of N. Aftab

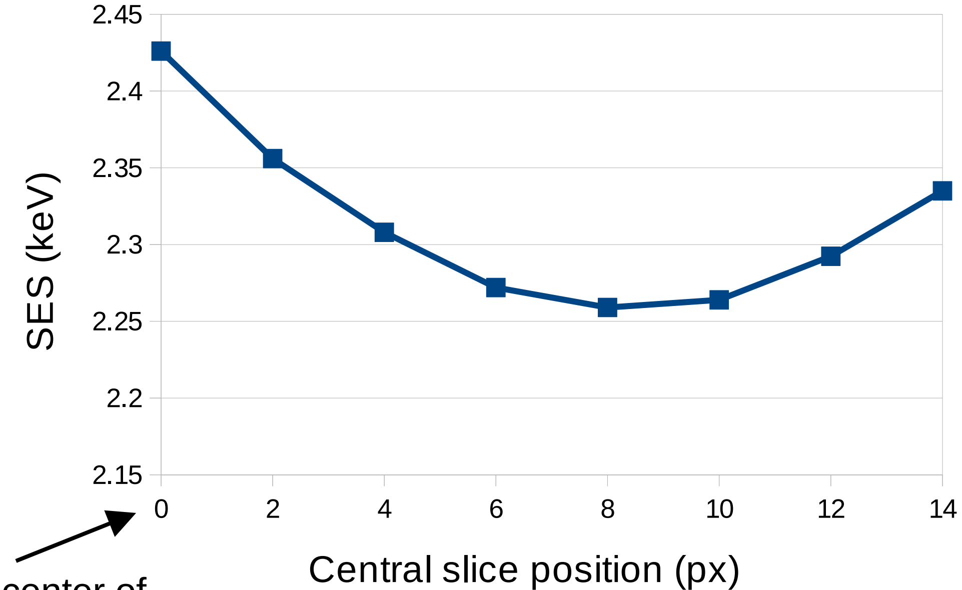
Thank you

Determining the central slice

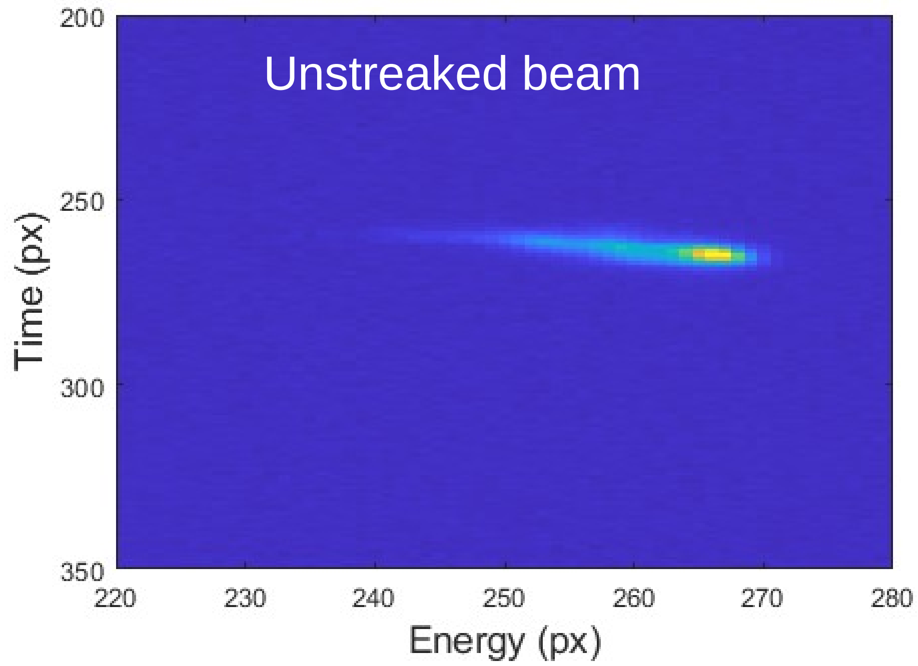
Need definition of central slice that accounts for position drift

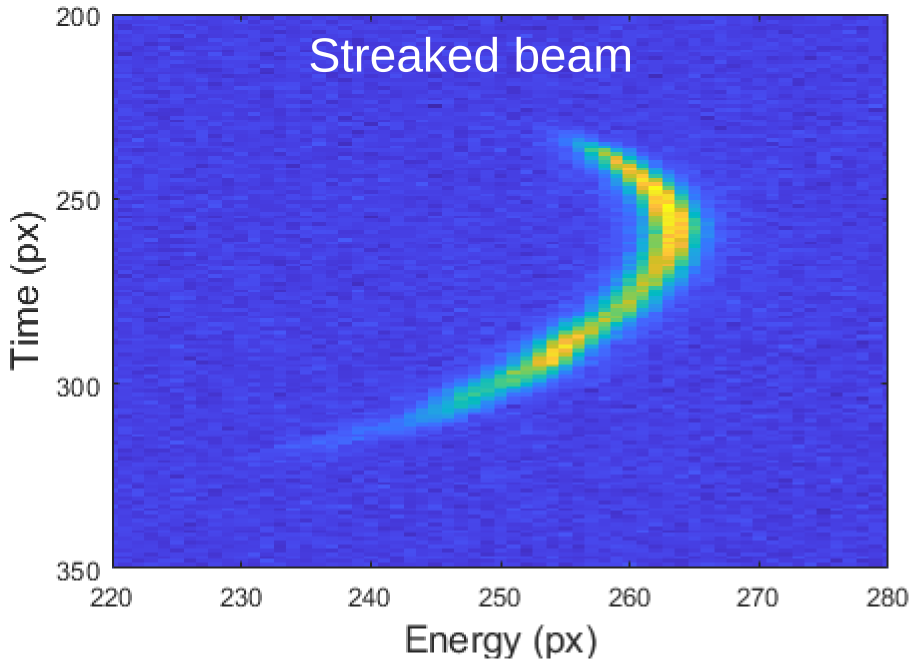
Methodology

- Initial guess: the center of the unstreaked beam
  - i.e. the beam center if the TDS is turned off
- Scan the slice location to find the minimum SES



0 = center of unstreaked beam

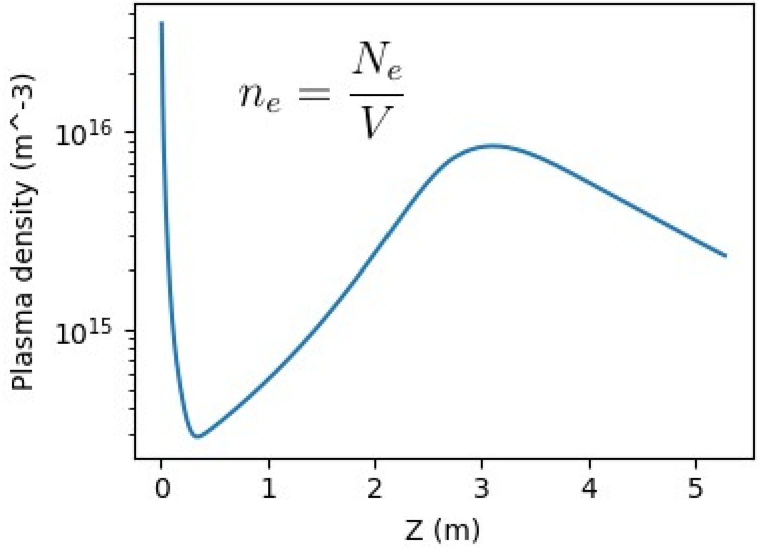




Estimating IBS from plasma parameters

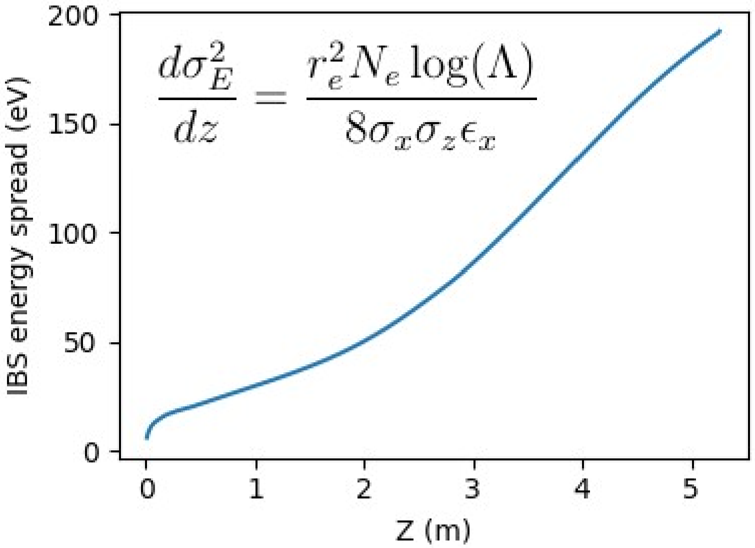
Plans for further investigations and improvements to the setup

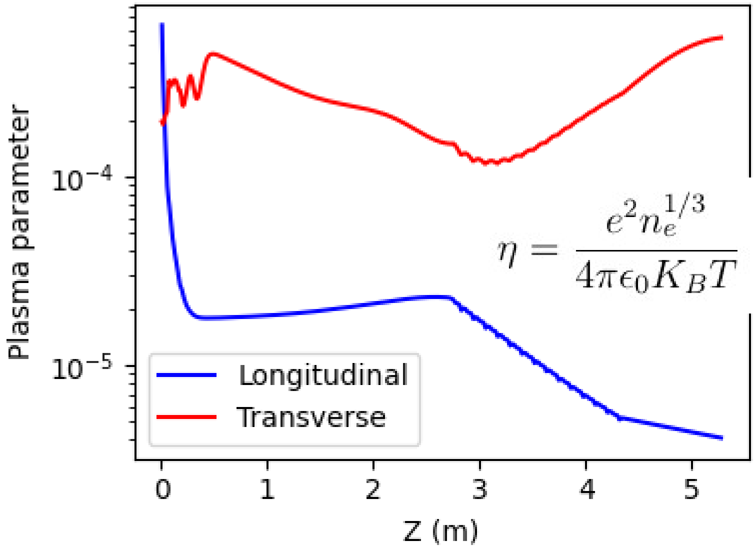
- Using crude model of static, neutralized plasma to calculate the beam density, temperature, plasma parameter, and IBS energy spread
  - Use rms parameters from beamline simulations to calculate values
  - Estimate ~0.2 keV SES increase at Slit1 from IBS
- See sharp increase in plasma parameter near the cathode
  - Possible collisions at cathode increases SES?

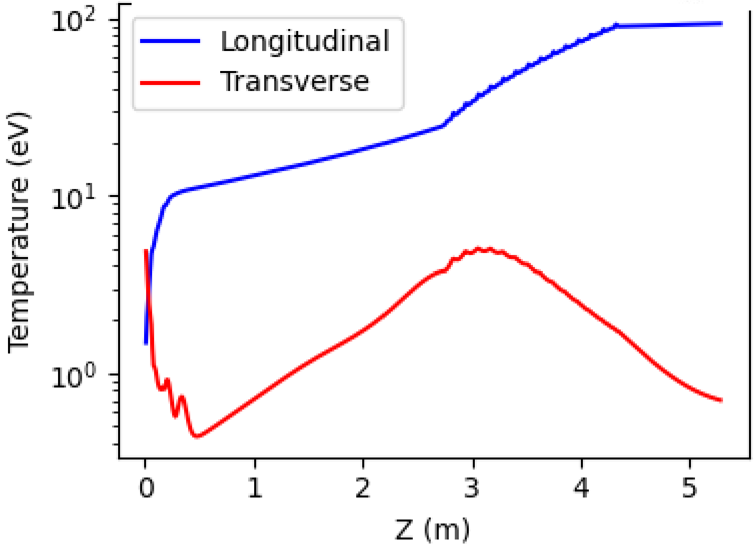


$$k_B T_{\parallel} = \frac{1}{2} m c^2 \left\langle \tilde{\beta}_z^2 \right\rangle \approx \frac{\epsilon_z^2}{m c^2 \sigma_z^2}$$

$$k_B T_{\perp} = \frac{1}{2} m c^2 \cdot 2 \left\langle \tilde{\beta}_x^2 \right\rangle \approx 2 m c^2 \frac{\epsilon_x^2}{\sigma_x^2}$$







Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Chris Richard
DESY PITZ
christopher.richard@desy.de