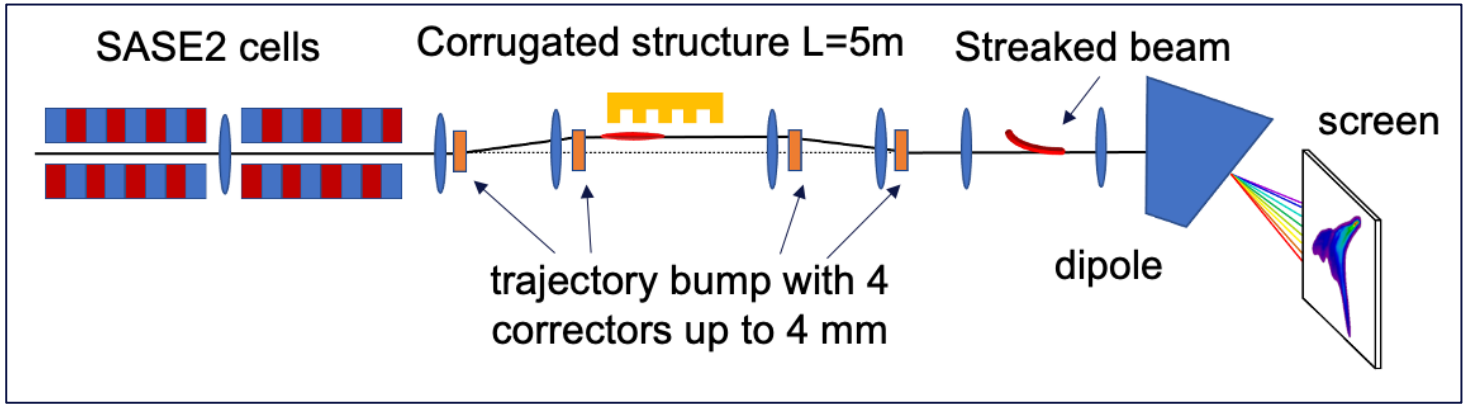
Measurement of quantum diffusion in an electron beam

S. Tomin, E. Schneidmiller, W. Decking

DESY

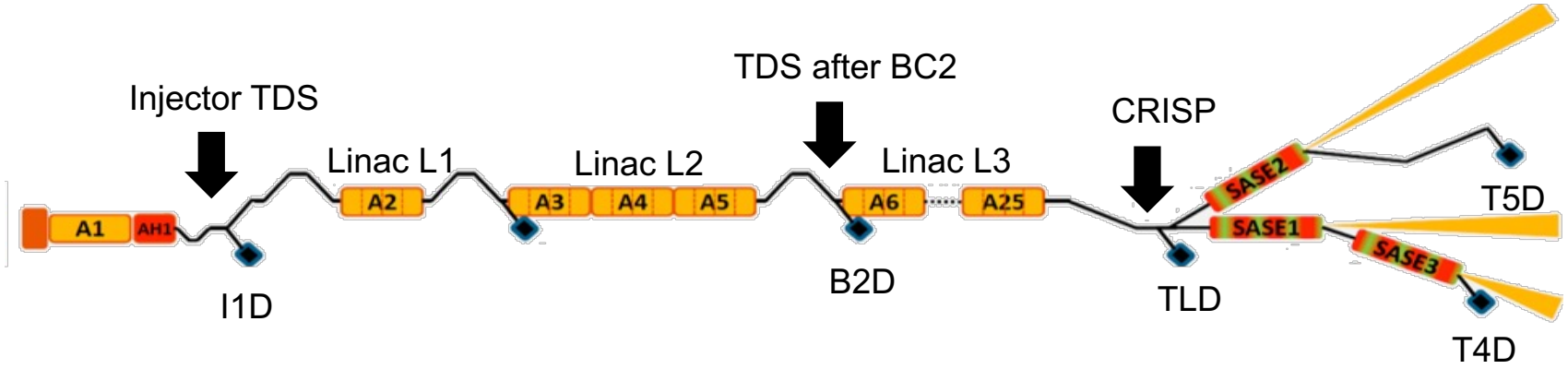
Beam dynamics meeting, 3 May 2021



Outline

- Introduction
- Diagnostic corrugated structure for SASE2 beamline
- Quantum diffusion measurement
- Summary

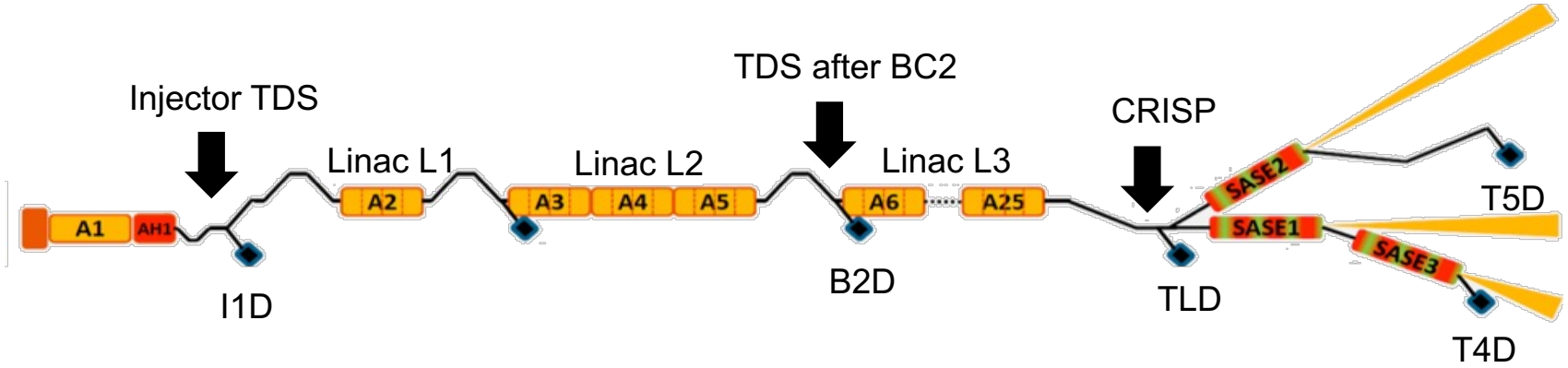
Longitudinal phase space diagnostics at the European XFEL accelerator



- Injector TDS
- BC2 TDS
- CRISP - THz Spectrometer for Bunch Length Characterization

- LPS measurements **after the undulator** are of high interest for FEL and beam dynamics studies and facility operation

Longitudinal phase space diagnostics at the European XFEL accelerator



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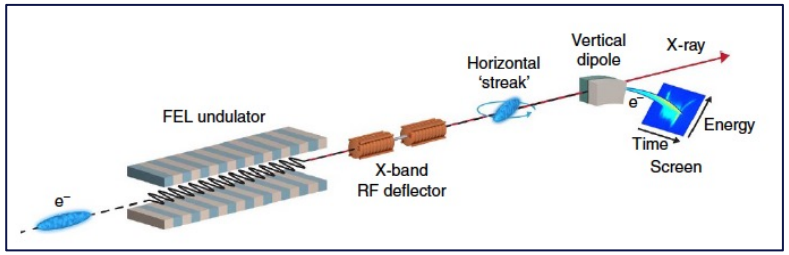
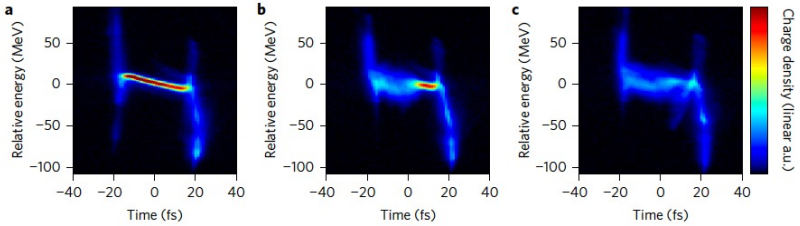
- **TDS after undulator, e.g. SLAC LCLS-I**

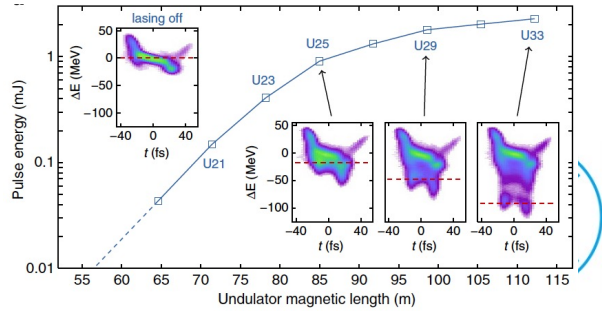


Fresh-slice multicolour

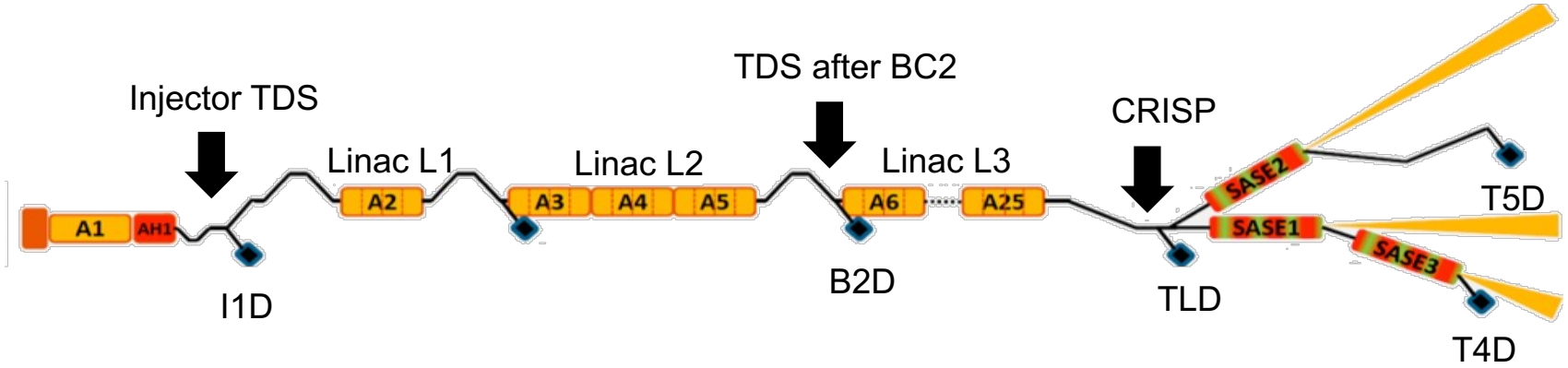


Nature Photonics **10**, pages 745–750 (2016)

Nat. Commun. 5, 3762 (2014)



Longitudinal phase space diagnostics at the European XFEL accelerator



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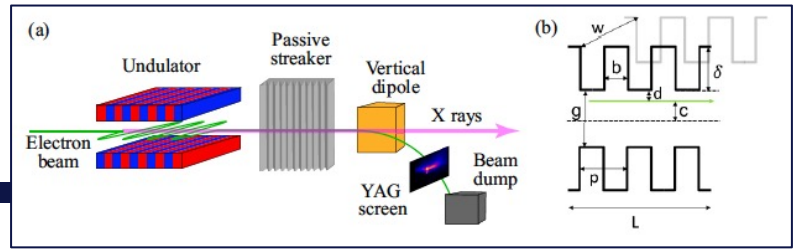
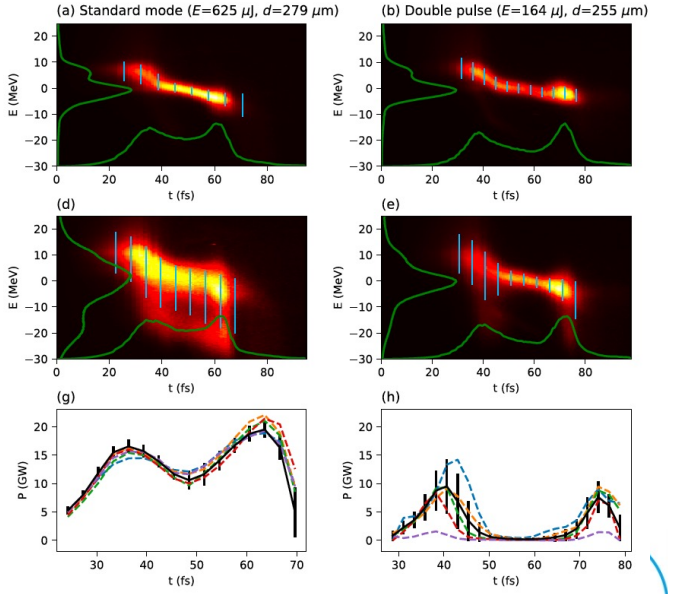
- TDS after undulator, e.g. SLAC LCLS-I
- **Wakefield structure, e.g. PSI SwissXFEL**





Phys. Rev. Res. 4, 013017 (2022)

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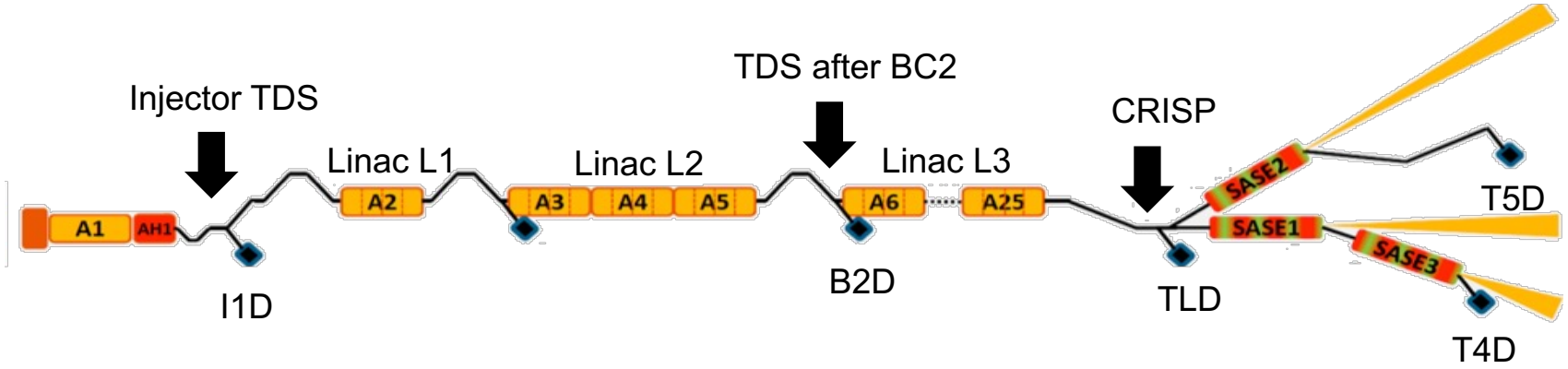
Longitudinal phase space diagnostics at the European XFEL accelerator



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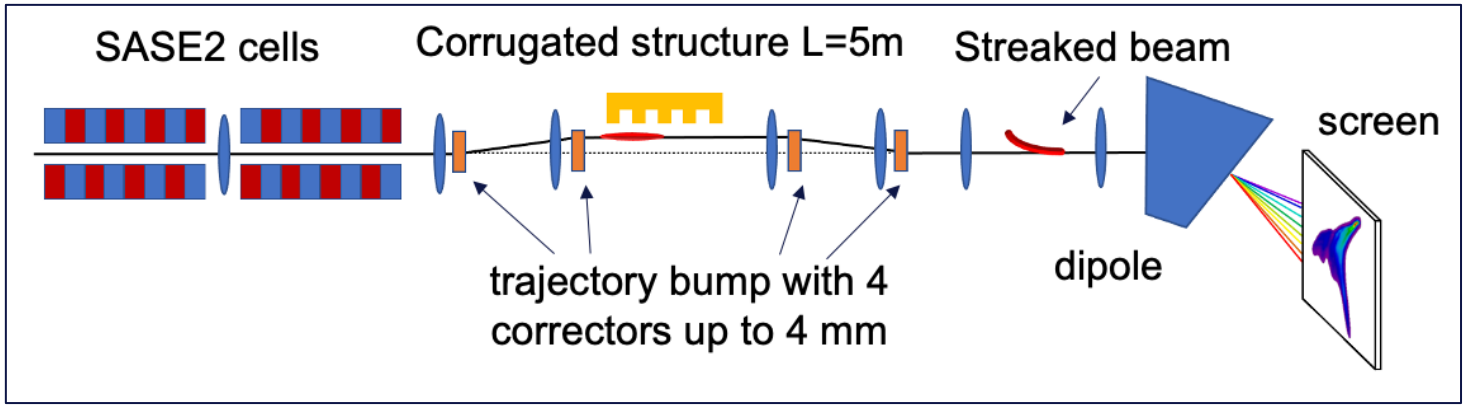
- LPS measurements **after the undulator** are of high interest for FEL and beam dynamics studies and facility operation
- TDS after undulator, e.g. SLAC LCLS-I
- Wakefield structure, e.g. PSI SwissXFEL

- TDS - linear device = easier to analyze data, but the development requires a significant investment of time, manpower and money
- Wakefield structure – nonlinear device = required special technics to analyze data, but is cheap to produce and operate

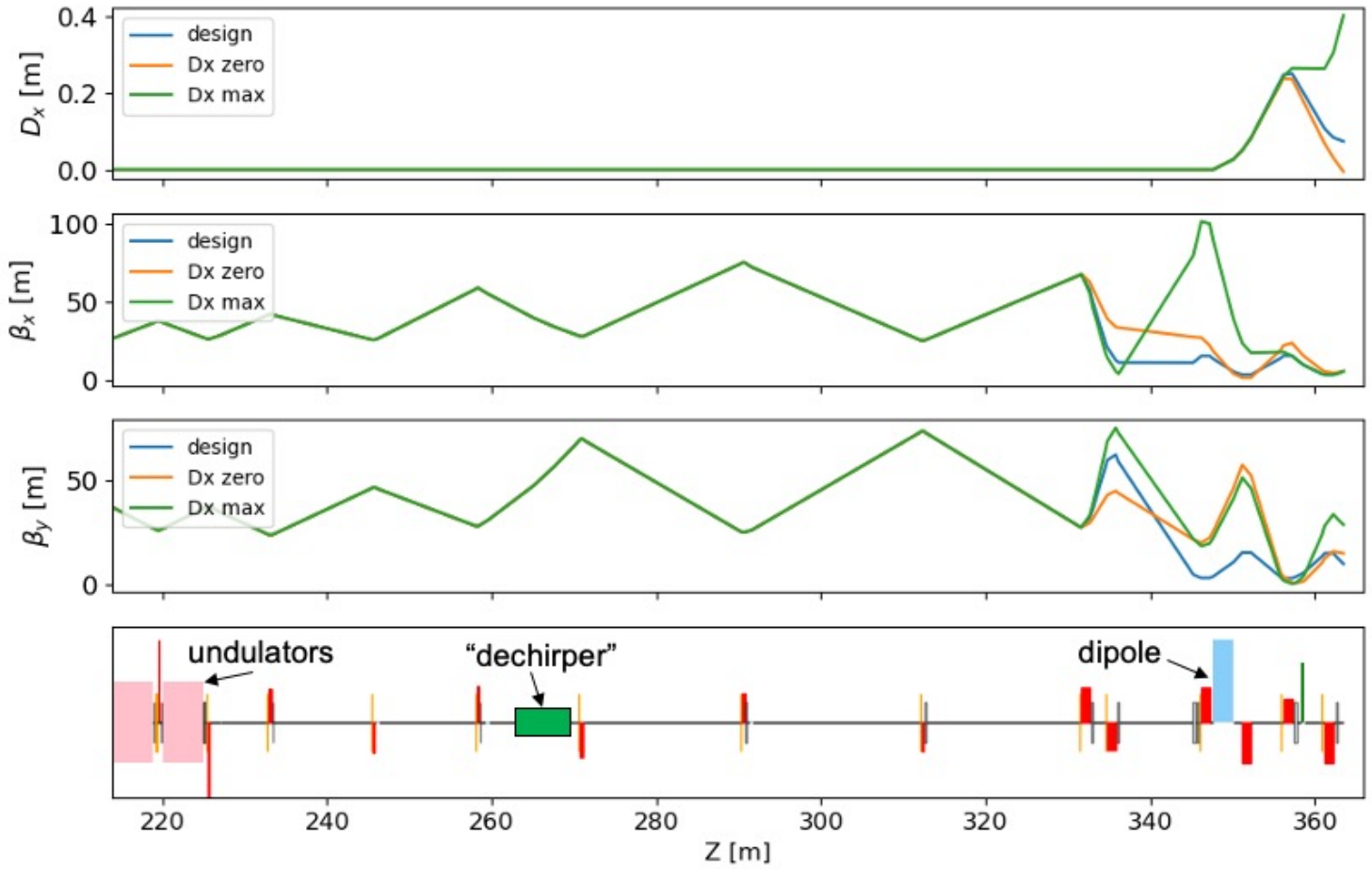
Diagnostics corrugated structure after SASE2 undulator

- Currently after SASE2 there are no undulators
  - No interference with users on other beamlines
- There are long drifts for dechirper installation and an ark with dispersion section (screen installation)
- Moving the electron beam to the corrugated plate using a trajectory bump instead of using a moving jaw as in PSI, SLAC
  - Considerable simplification of dechirper design
- What is needed for installation:
  - Only three vertical correctors (bump in vertical plane)
  - Screen in dispersive section
  - Dechirper

Dispersion in horizontal plane → kick in vertical



Beam optics modes for measurements



Parameters or optics modes

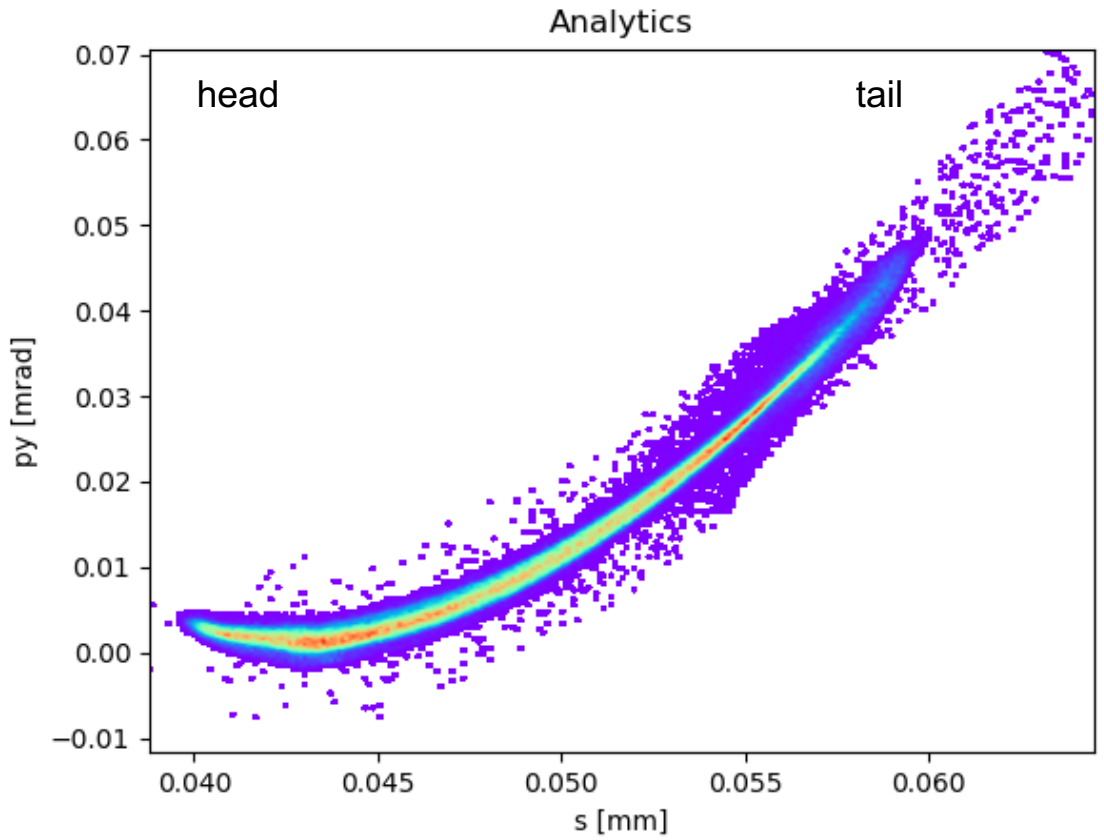
Mode	β_y^{WS}	D_x^{scr}	β_x^{scr}	β_y^{scr}	$\Delta\mu_y$	R_{34}
Design	56.4 m	7 cm	5.6 m	10.2 m	289 deg	-22.6
Zero dispersion	56.4 m	<1 cm	5.26 m	15 m	283 deg	-39.2
Max dispersion	56.4 m	40 cm	5.5 m	28.8 m	284 deg	-39.1

- Optics with zero dispersion are designed for energy resolution measurements (see next slides)

Nina Golubeva

Modeling transverse kick by dechirper

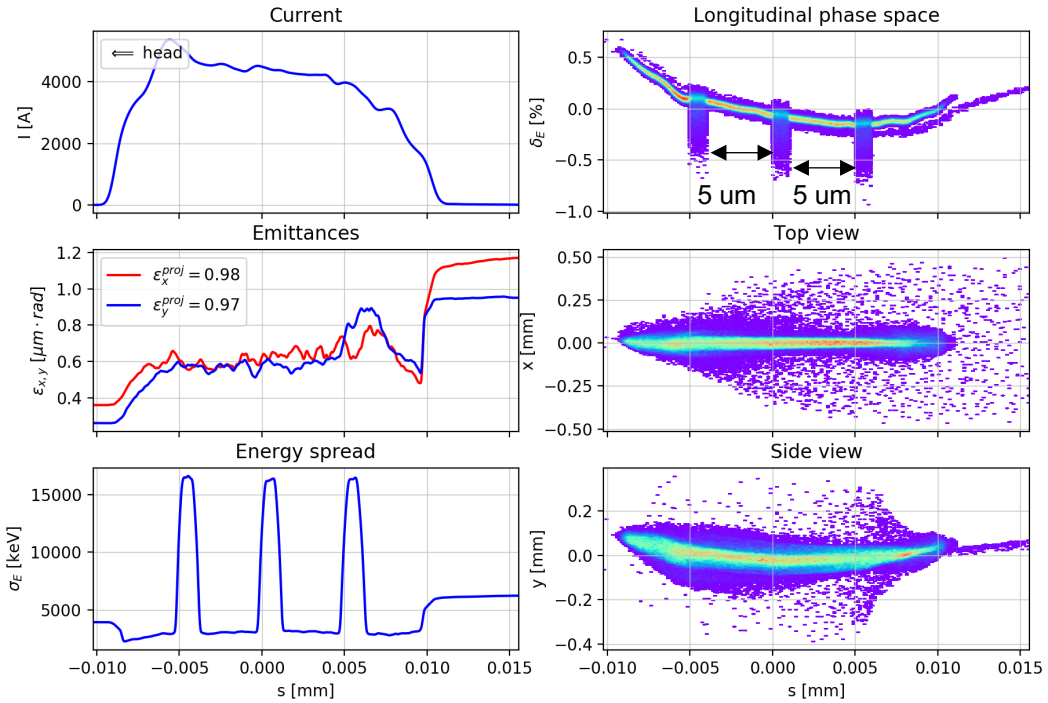
- Distance between beam and corrugated plate (4m long in simulations) 500 um



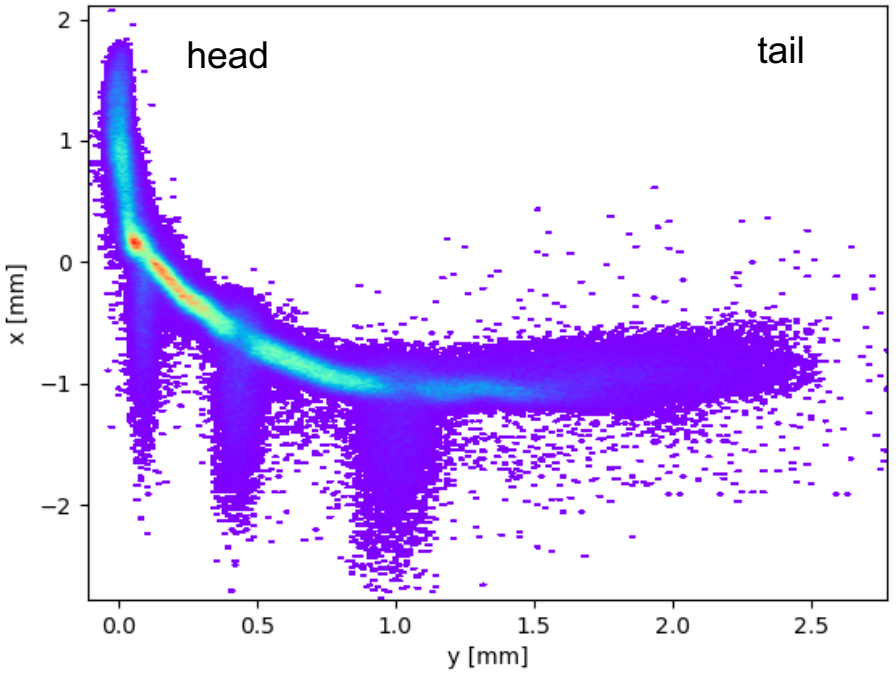
Modeling transverse kick by dechirper

- Distance between beam and corrugated plate (4m long in simulations) 500 um
- Tracking with OCELOT
  - 3D wakefields for dechirper was calculated based on analytical formulas (*https://doi.org/10.1016/j.nima.2016.09.001 and SLAC-PUB-16881*)
- Artificially induced energy spread +5 and – 25 MeV in 3 slices with width 1 μm and in positions $\pm 5\ \mu m$

Beam before dechirper

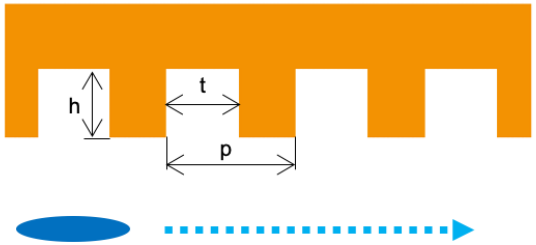


Picture on the screen with special beam optics



Corrugated structure in real life

- Segment length – 1 m
- Number of segments – 5
- Width of the plate – 12 mm



h [mm]	t [mm]	p [mm]
0.5	0.25	0.5

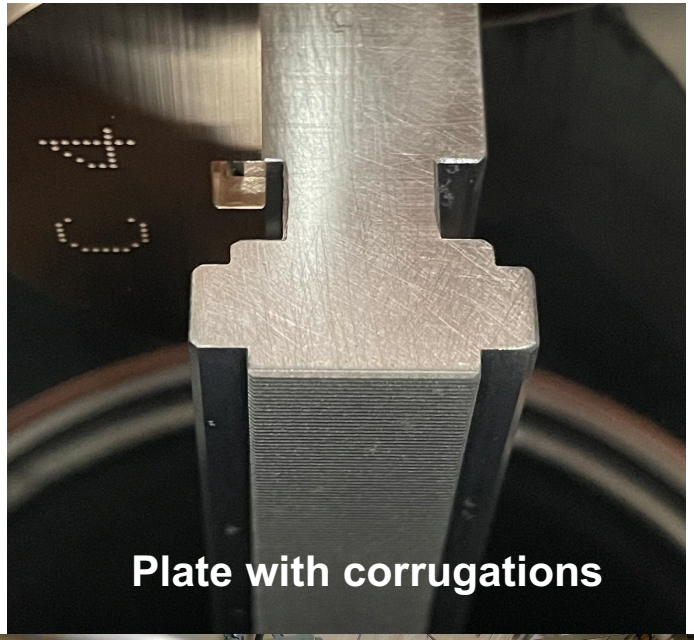
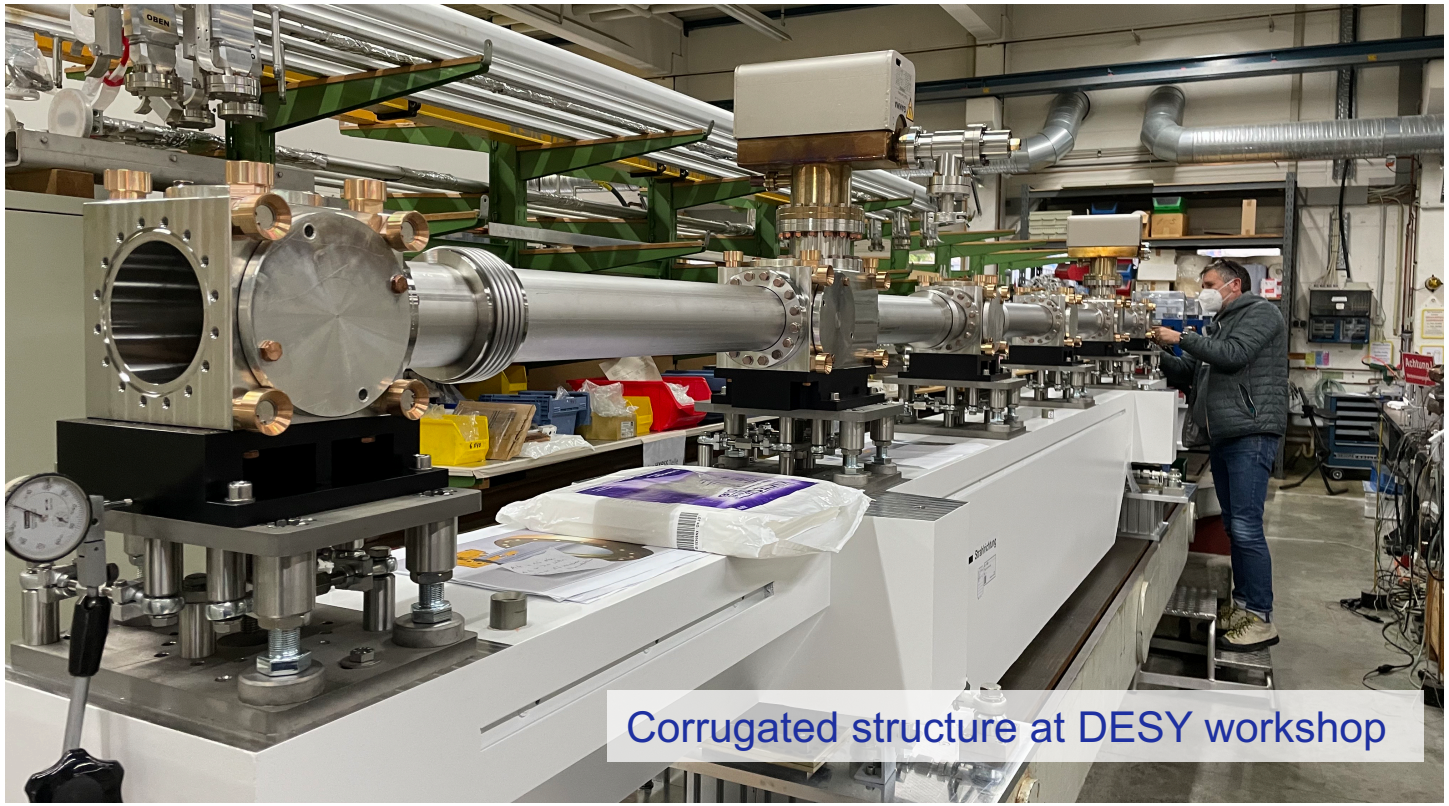


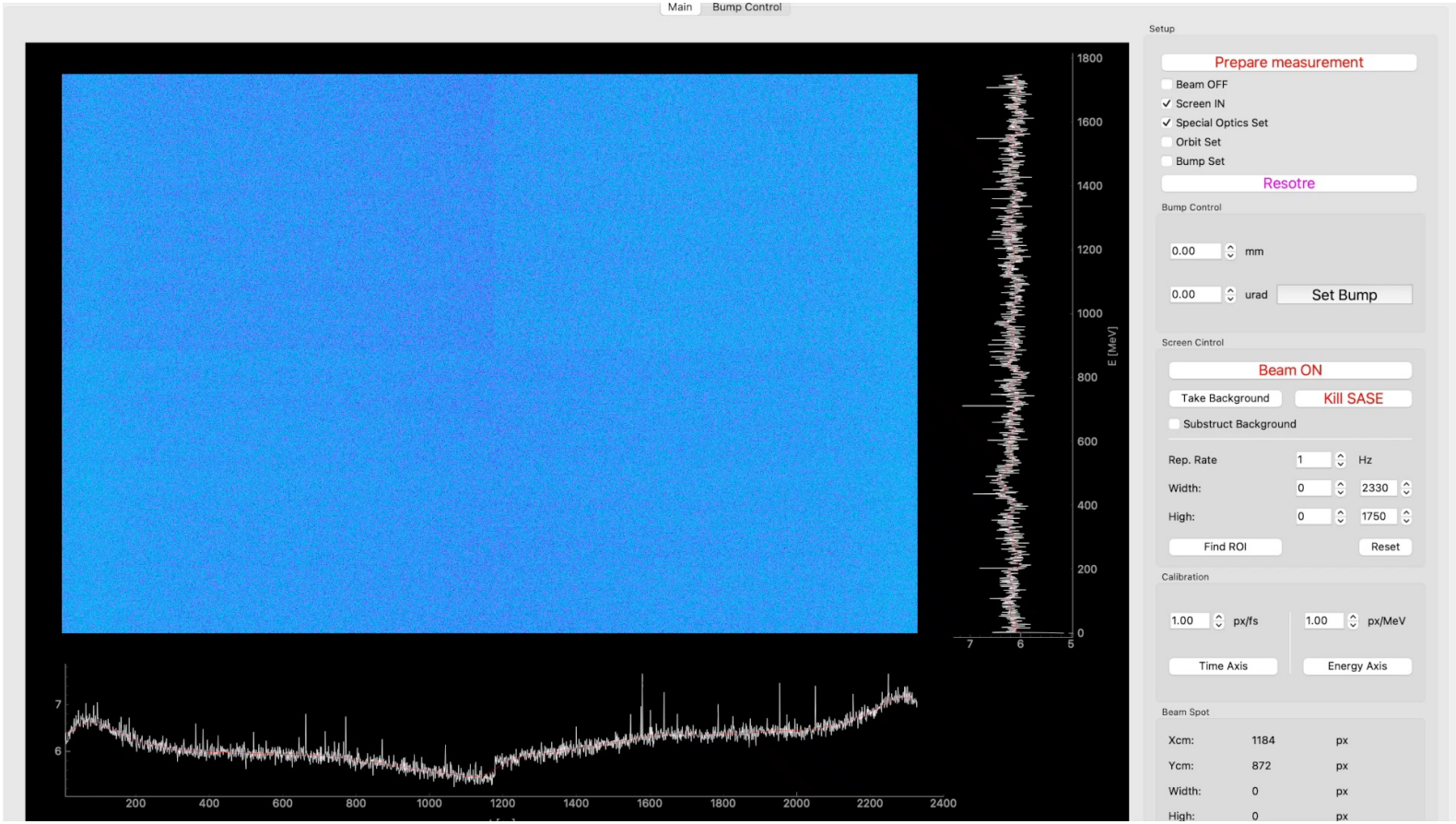
Plate with corrugations


Corrugated structure at DESY workshop

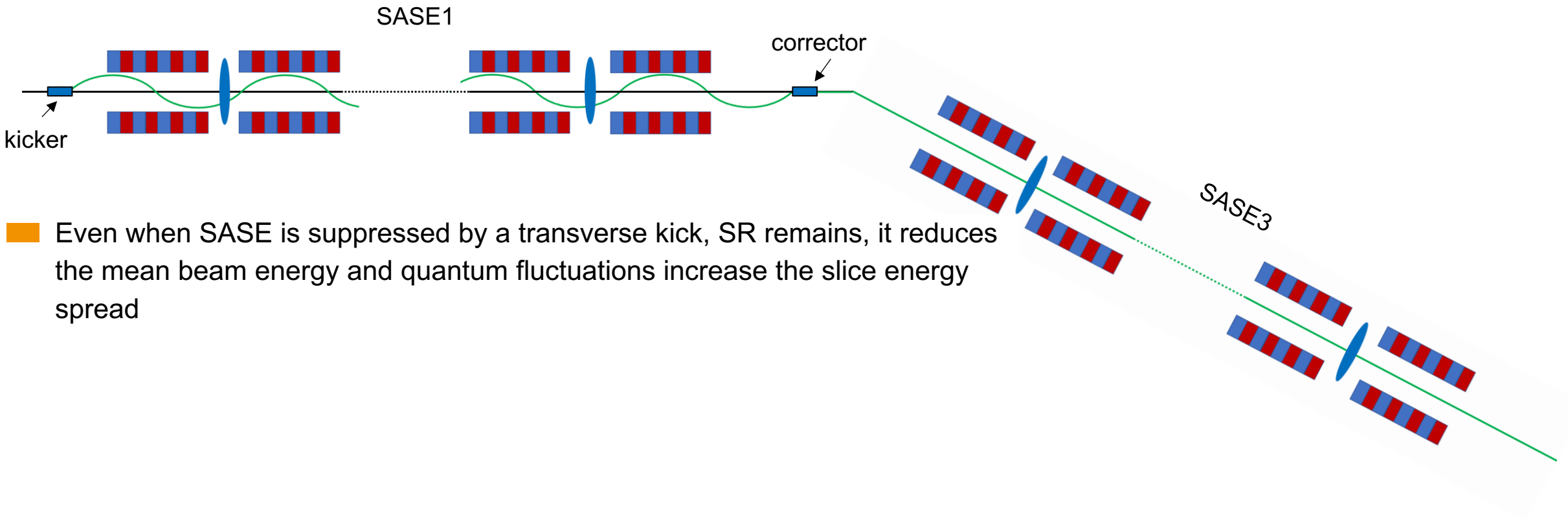

Corrugated structure at the tunnel

Commissioning

- Installation: December 2021
- Commissioning: 27 and 30 January 2022
- Dechirper tool was developed
  - Optics change
  - Bump control
  - Orbit control in the SA2 undulator for SASE suppression
  - Screen control
  - Energy calibration
  - Image processing



Quantum diffusion in an electron beam



- Even when SASE is suppressed by a transverse kick, SR remains, it reduces the mean beam energy and quantum fluctuations increase the slice energy spread

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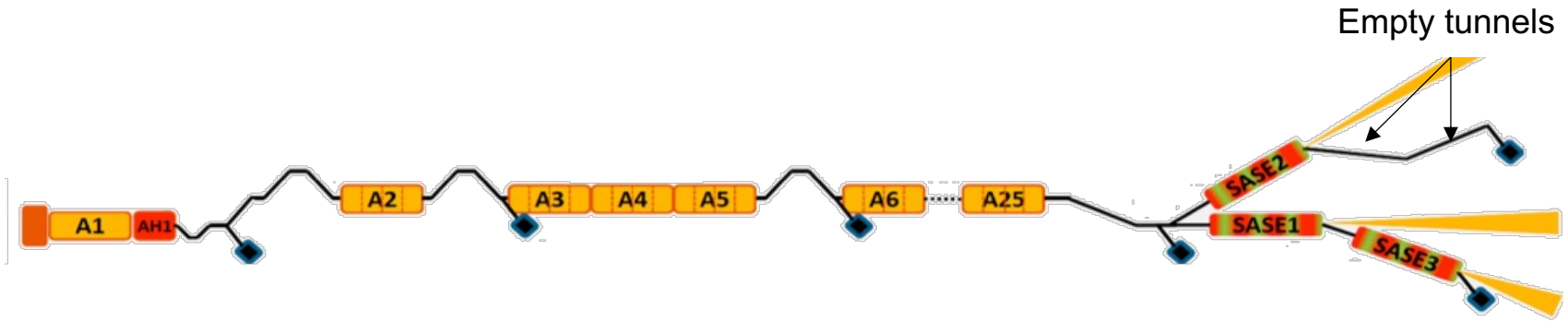


- Even when SASE is suppressed by a transverse kick, SR remains, it reduces the mean beam energy and quantum fluctuations increase the slice energy spread
- There are 2 empty tunnels after SASE2
- The energy diffusion imposes a fundamental limit on a minimal achievable wavelength in the X-ray free electron Laser.
- Measurements of slice energy spread at different undulator configurations and verification with theory are development of the diagnostics with the dechirper

Quantum diffusion in an electron beam

$$\frac{d\left\langle(\delta\gamma)^2\right\rangle}{dt} = \frac{7}{15} c\lambda\!\!\!^{-}_c r_e \gamma^4 k_w^3 K^2 F(K)$$

$$F(K) = 1.20K + \frac{1}{1 + 1.33K + 0.40K^2}$$

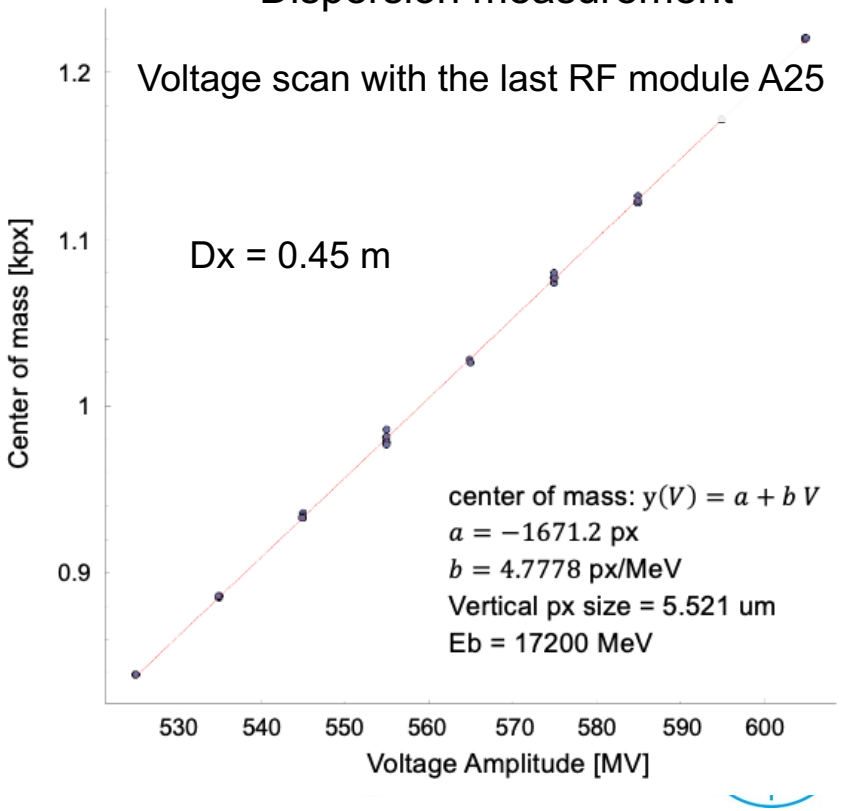
- Two measurements: dependence of energy diffusion on
  - the length of the undulator
  - the undulator K parameter

- $\sigma_{qd}(K,L) = \sqrt{\frac{L\, d\langle(\delta\gamma)^2\rangle}{cdt}} = \sqrt{\sigma_E^{slice}(K,L)^2 - \sigma_E^{slice}(0,0)^2}$

- Prerequisites:
  - Maximum beam energy to maximize effect: 17.2 GeV
  - Initial slice energy spread should be small = low current
  - Dispersion measurement in the screen position
  - Modeling of the experiment

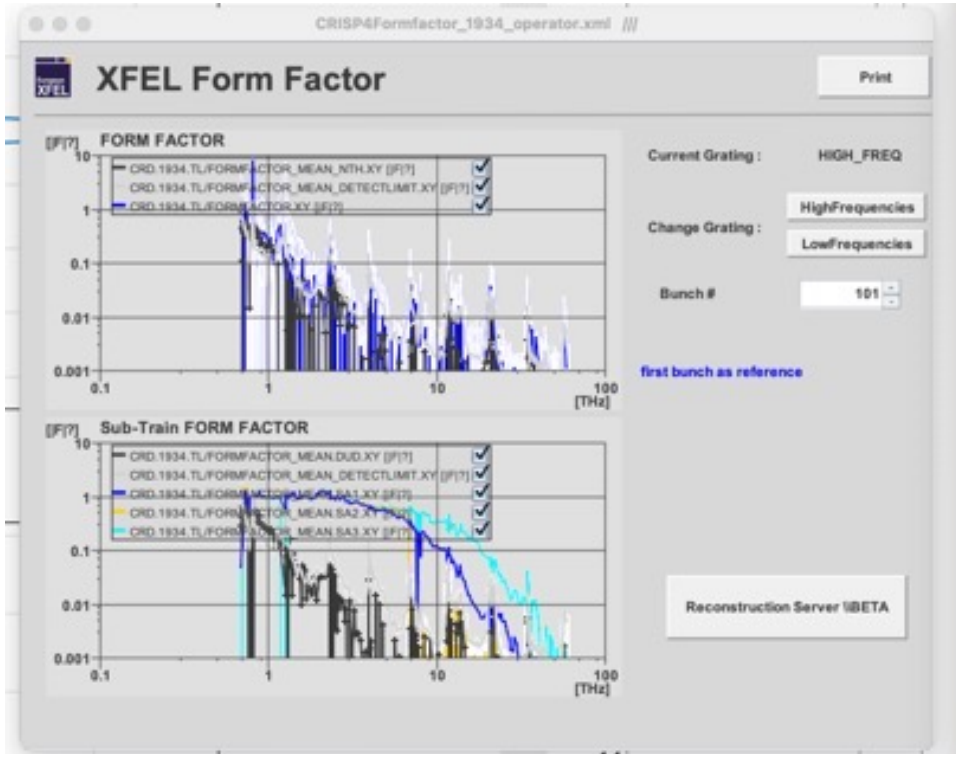
E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov,
Nucl. Instr. Meth. Phys. Res., Sect. A 381 (1996) 545-547

Dispersion measurement

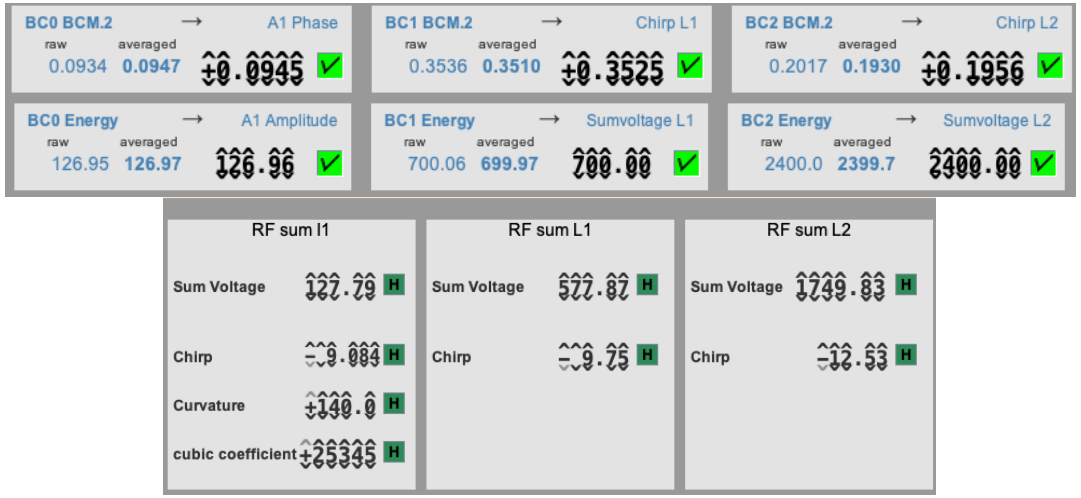


Compression settings

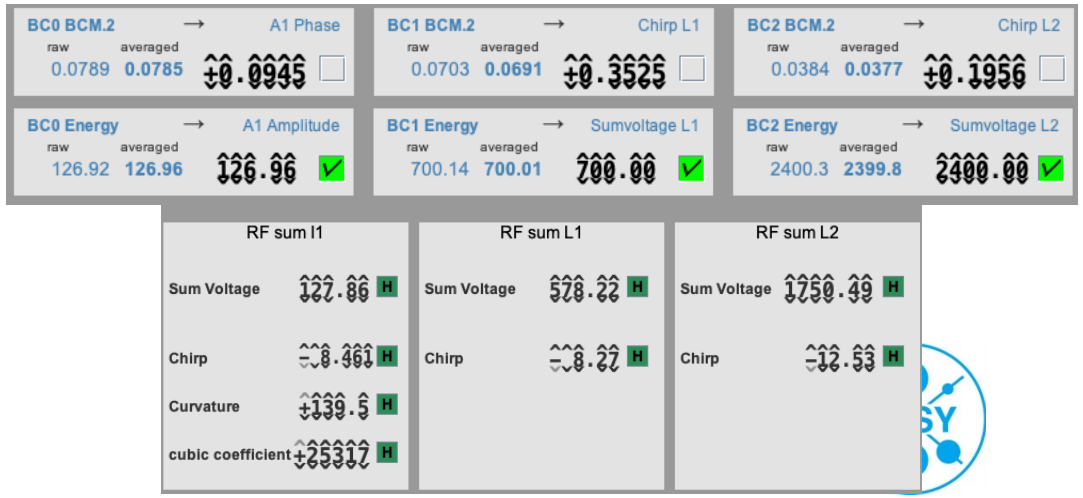
CRISP spectrum during measurements



Compression settings for normal operation

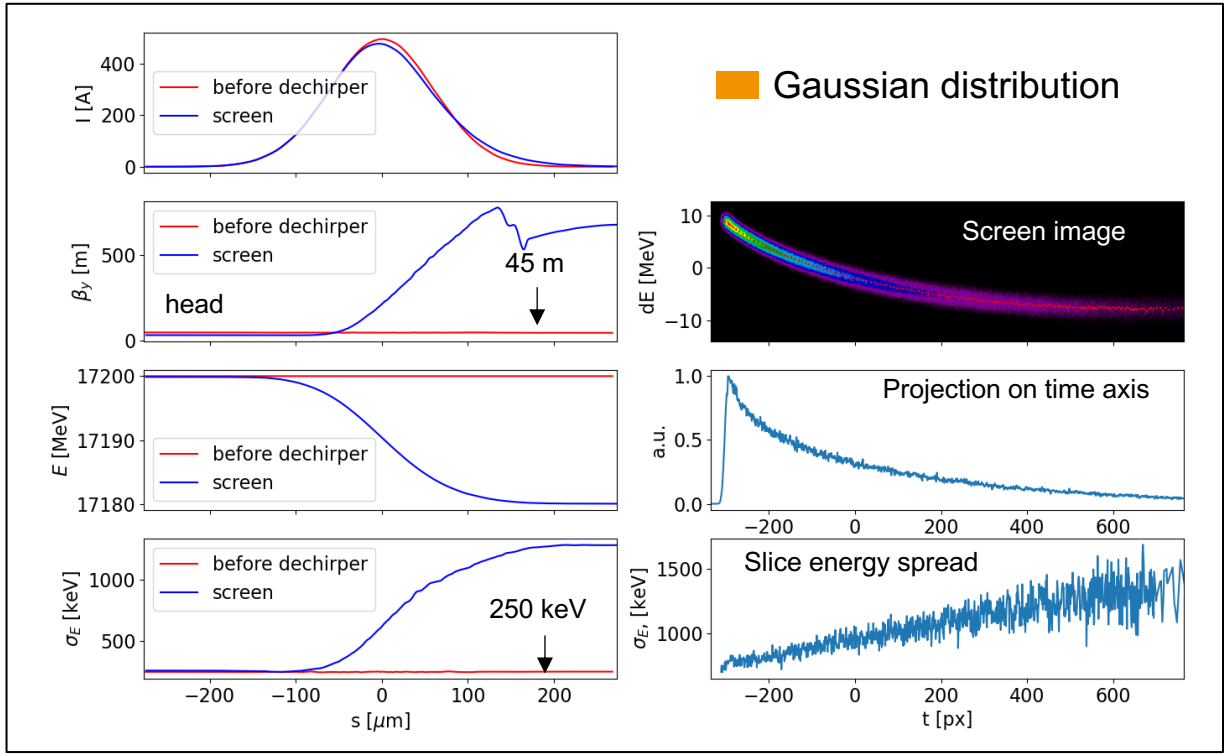


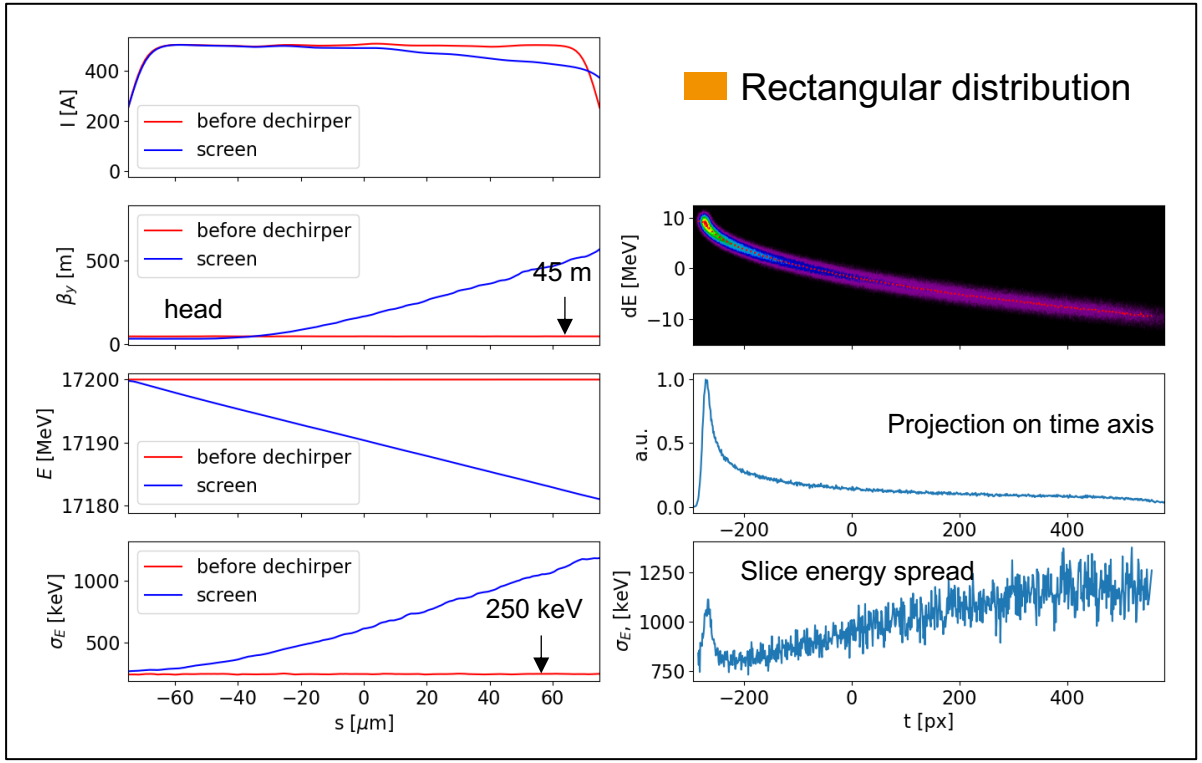
Compression setting during measurements



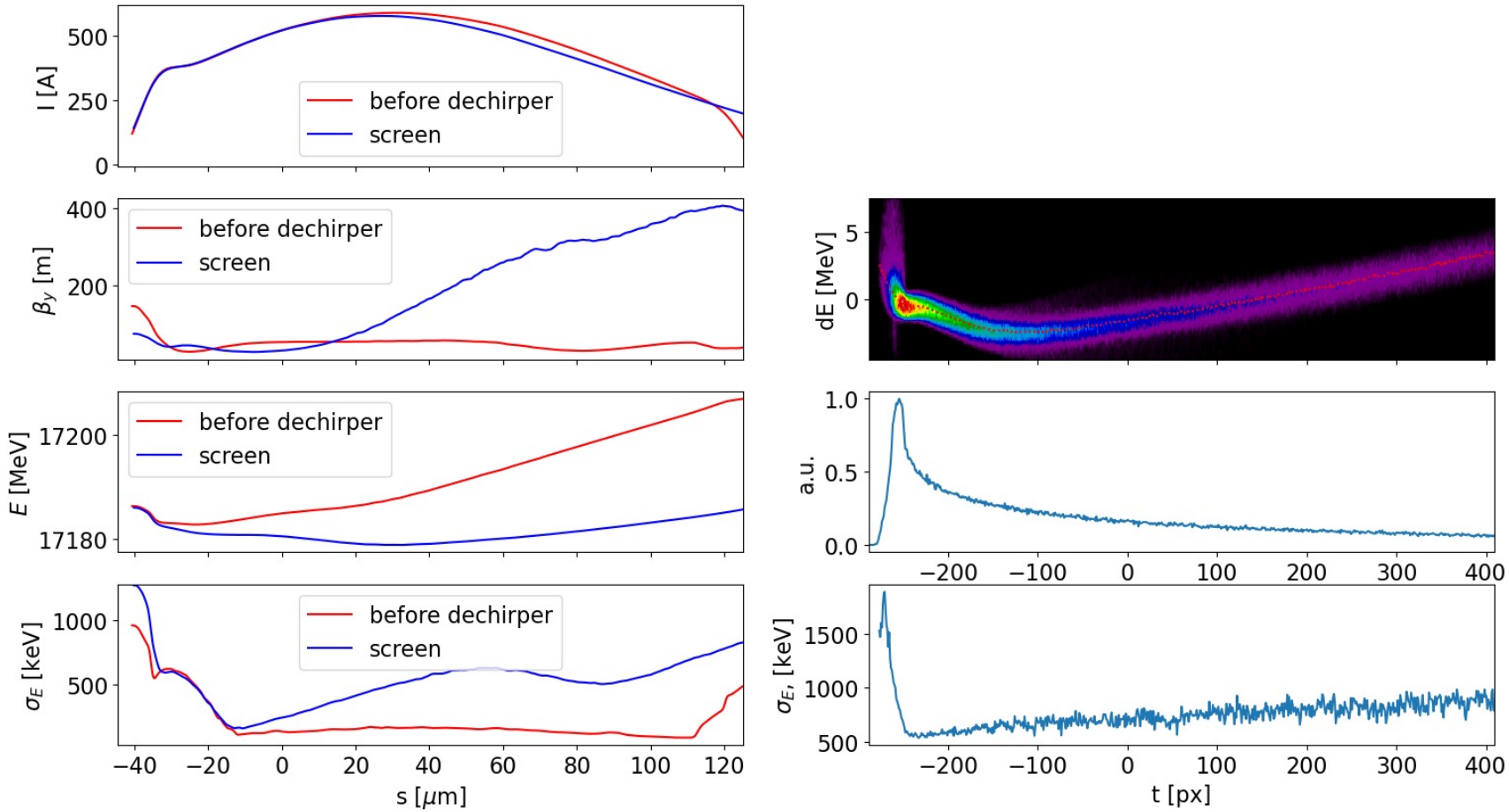
Modeling the effect of a dechirper on a beam with different current profiles

- The simulation was performed in Ocelot
- The initial slice parameters along the beam are flat



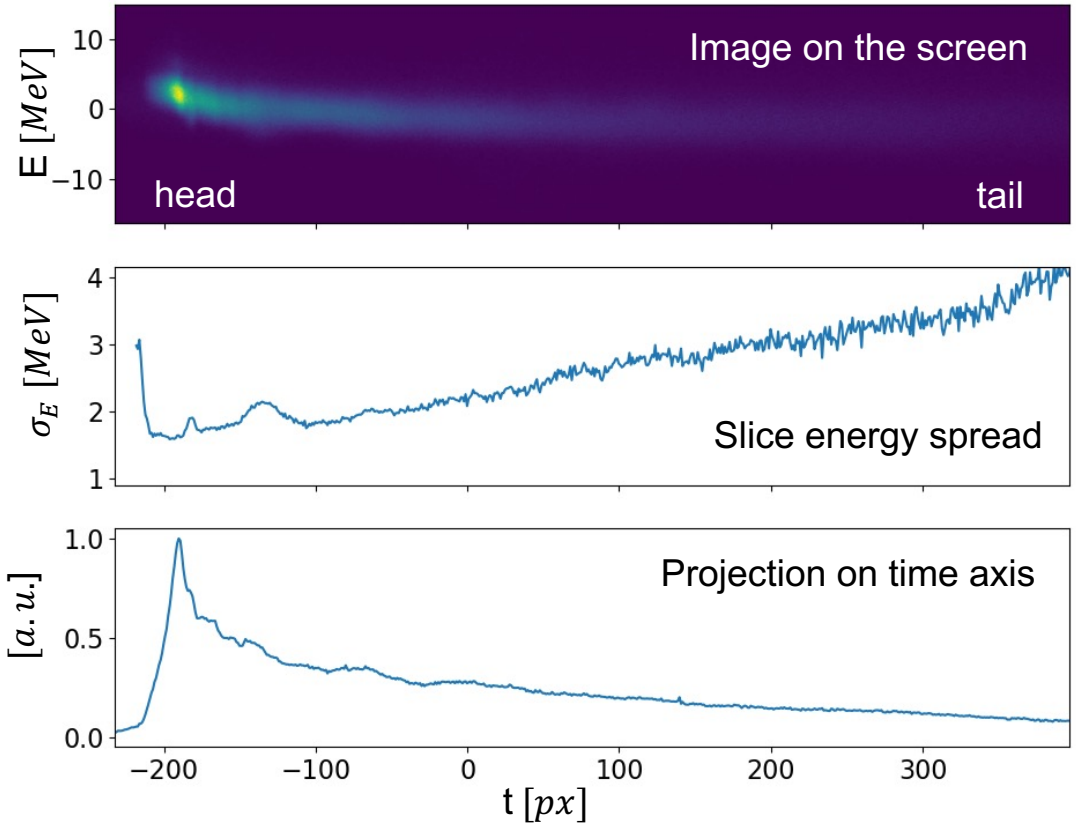


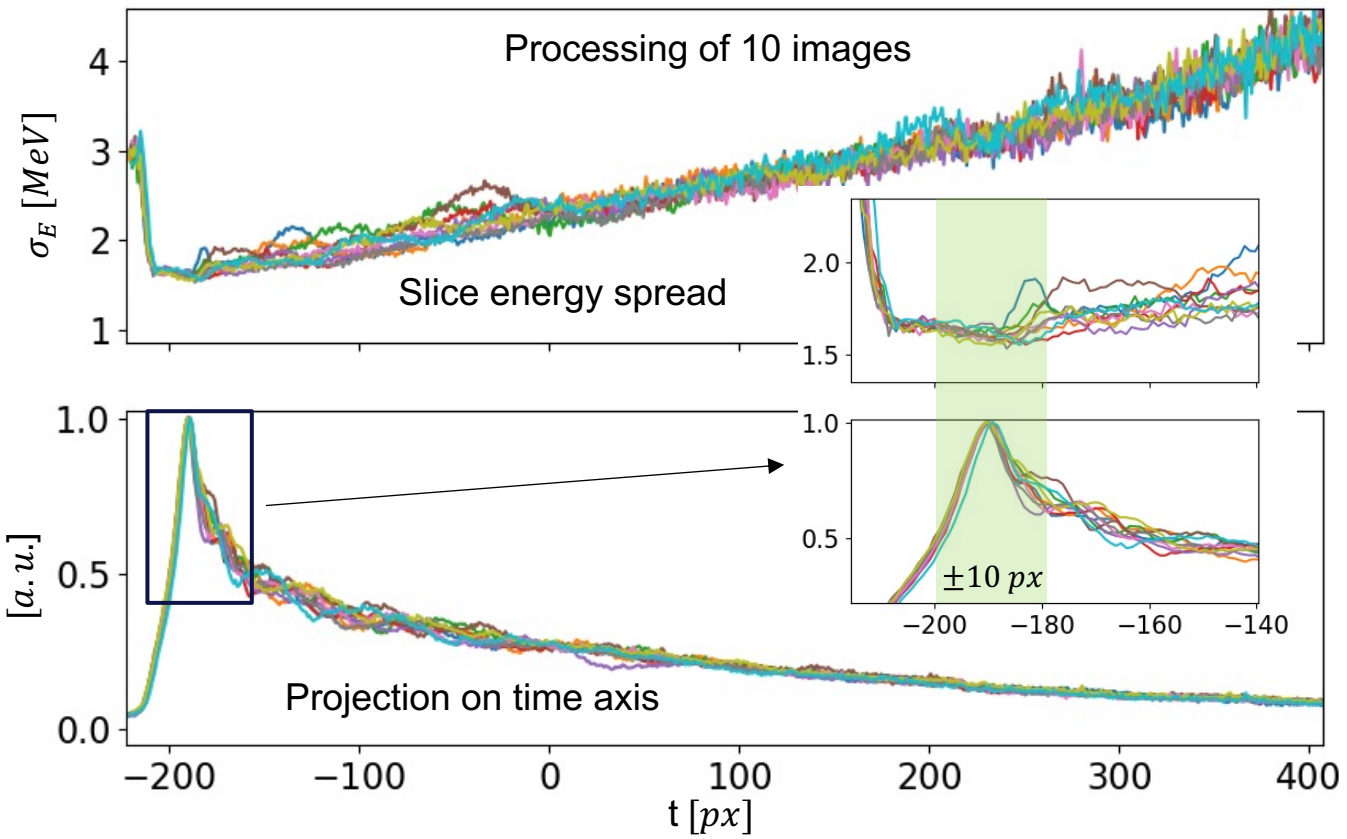
Simulations with BKR compression settings



Measurements of slice energy spread with open undulators

- On each step was taken 10 images





- Selected slice at the head of the beam with width $\pm 10\ px$
- Beam current < 1kA
- $\sigma_E^{slice} = 1.65\ \pm 0.02$ MeV

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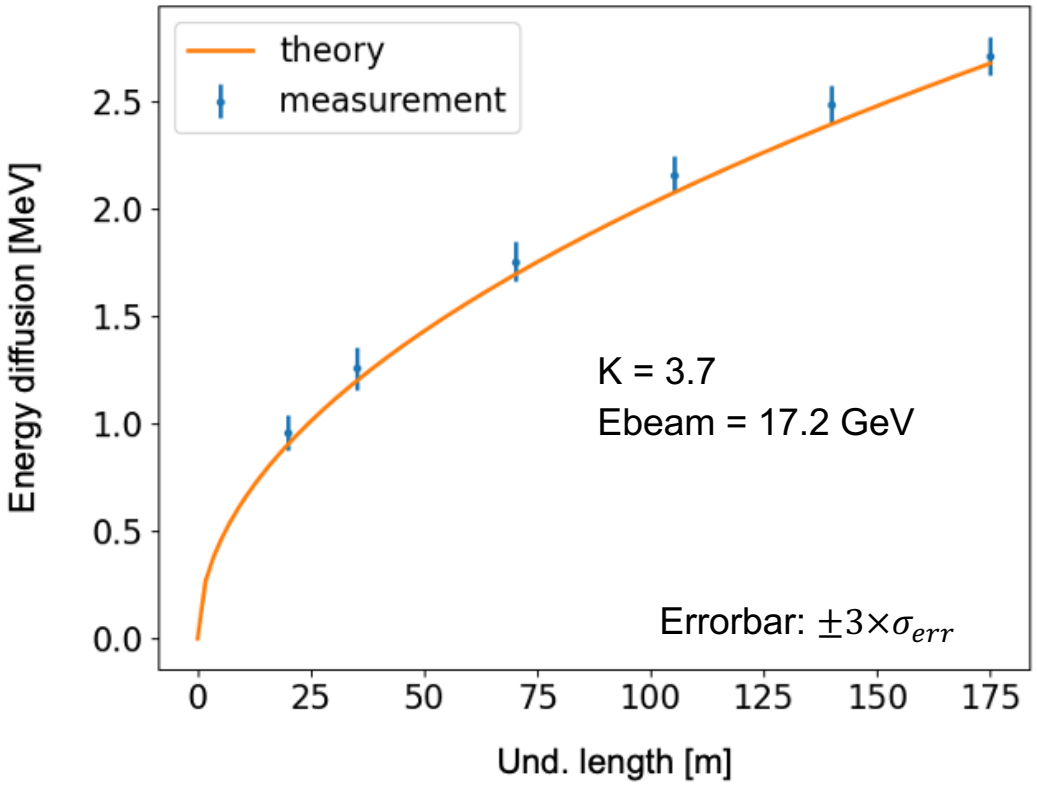
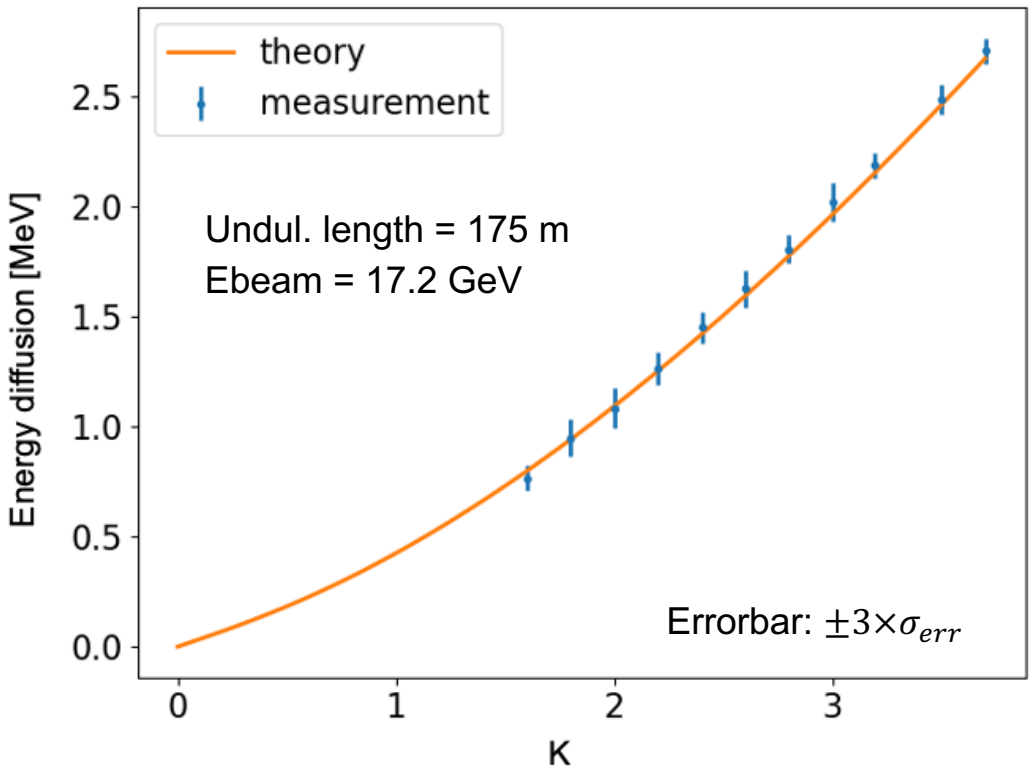
Quantum diffusion: results

quantum diffusion vs undulator length



quantum diffusion vs K

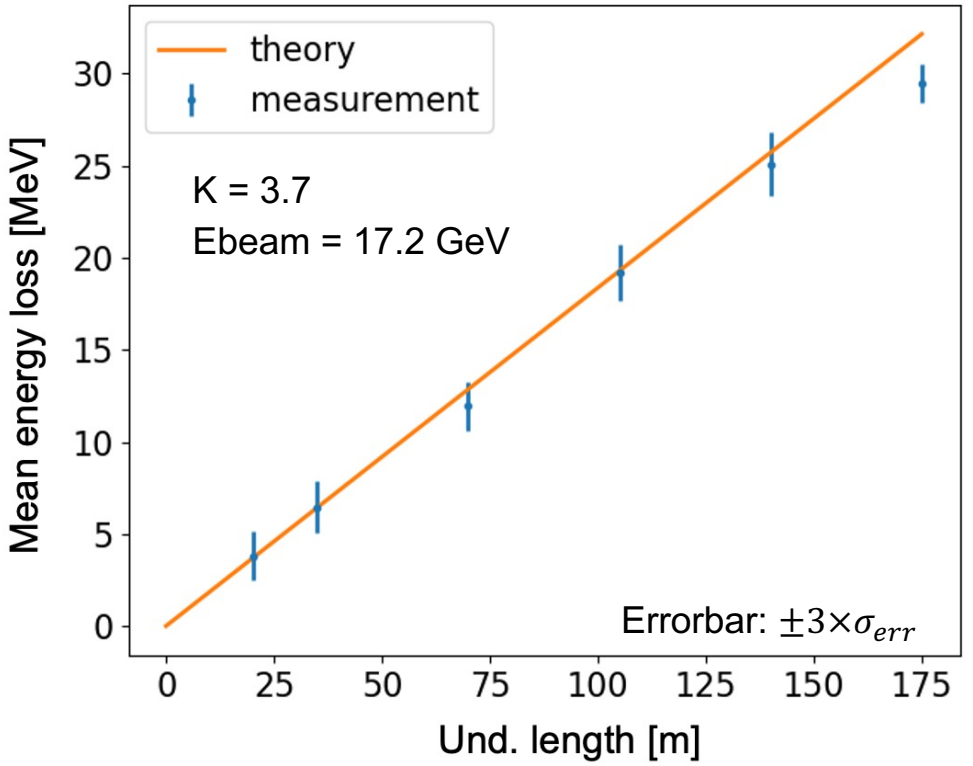


Mean energy loss due to SR

- Using the same data, the mean beam energy loss was calculated.

$$U = \frac{4\pi^2}{3}\frac{r_e E^2 K^2 L}{mc^2 \lambda_w^2}$$

- This serves to confirm the results of the dispersion measurements



Summary

- The quantum diffusion measurement agrees with theory
- Reconstruction is required to map nonlinear streaked beam image to “linear” space. Project is ongoing
- Already in use to observe various lasing modes
- 15 months between the first estimates and the first measurements on the accelerator (in the middle of a pandemic)

Diagnostic wakefield structure for SASE2 beam line

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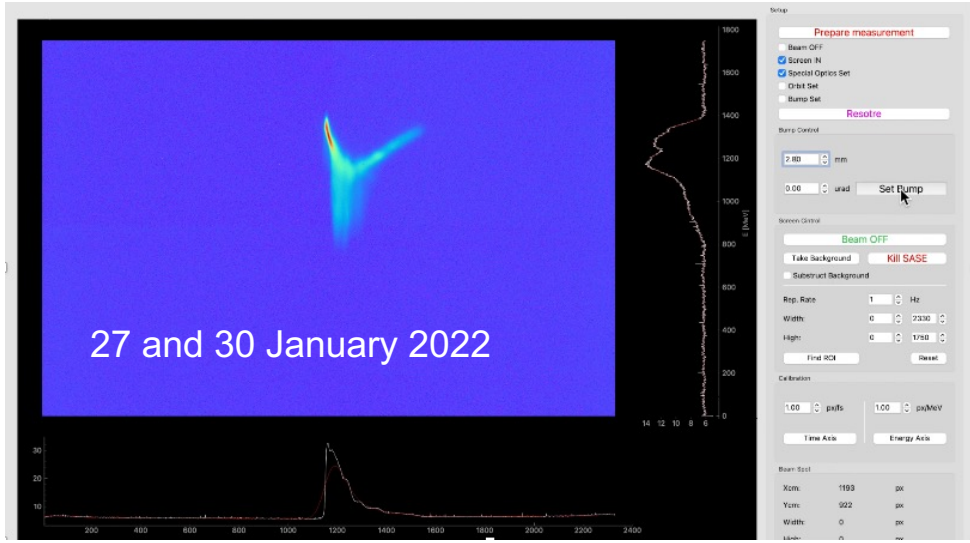
DESY

DESY S2E Seminar, 27 October 2020



Thank you for your attention