Time resolved transverse and longitudinal phase space measurements at the high brightness photo injector PITZ

1. Motivation
2. Transverse deflecting structure
3. Longitudinal phase space tomography
4. PITZ facility overview
5. Experimental results using tomographic technique
6. Conclusions and outlook

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August 19th, 2014

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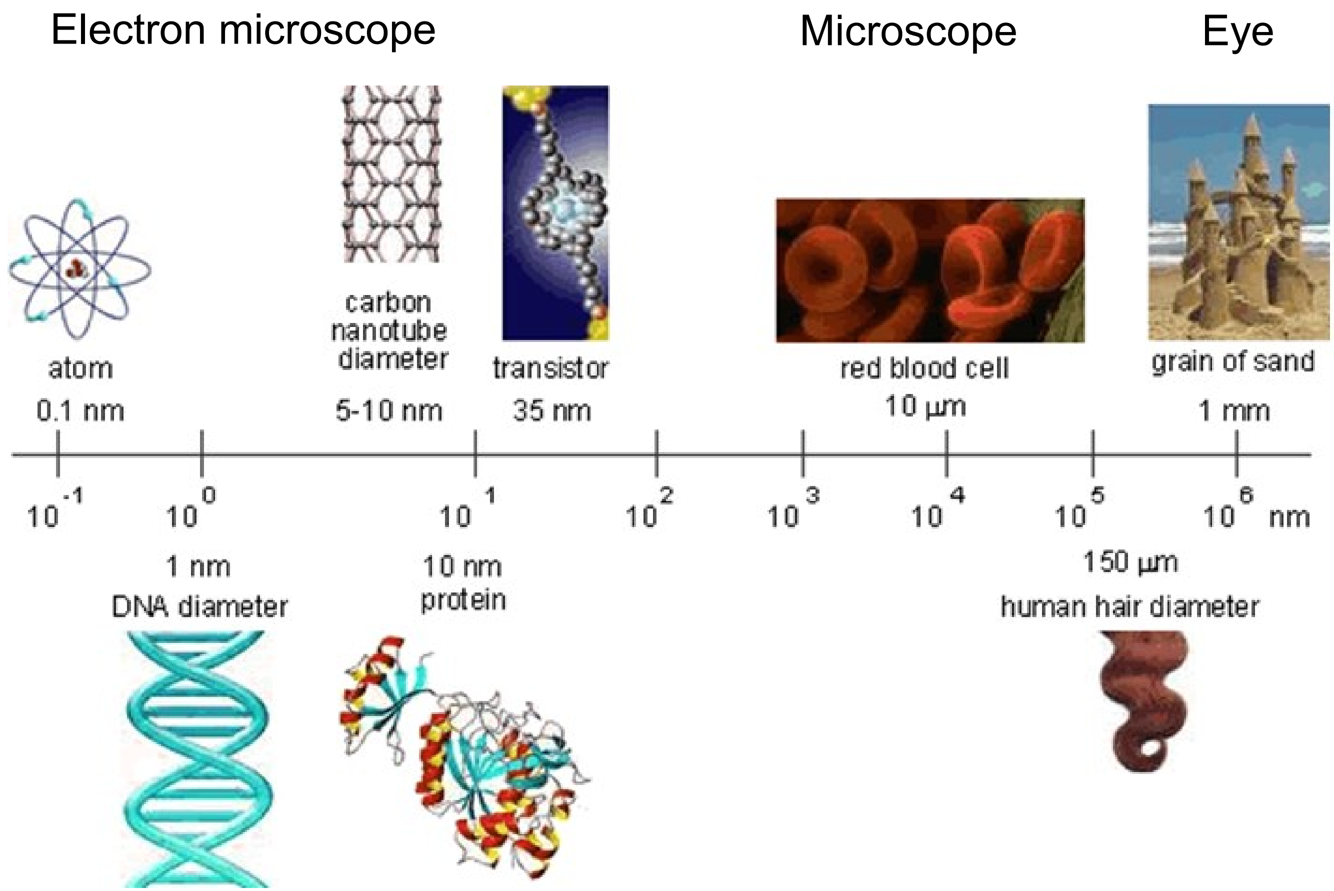
HELMHOLTZ GEMEINSCHAFT
PITZ Photo Injector Test Facility Zeuthen
DESY

Scale of length

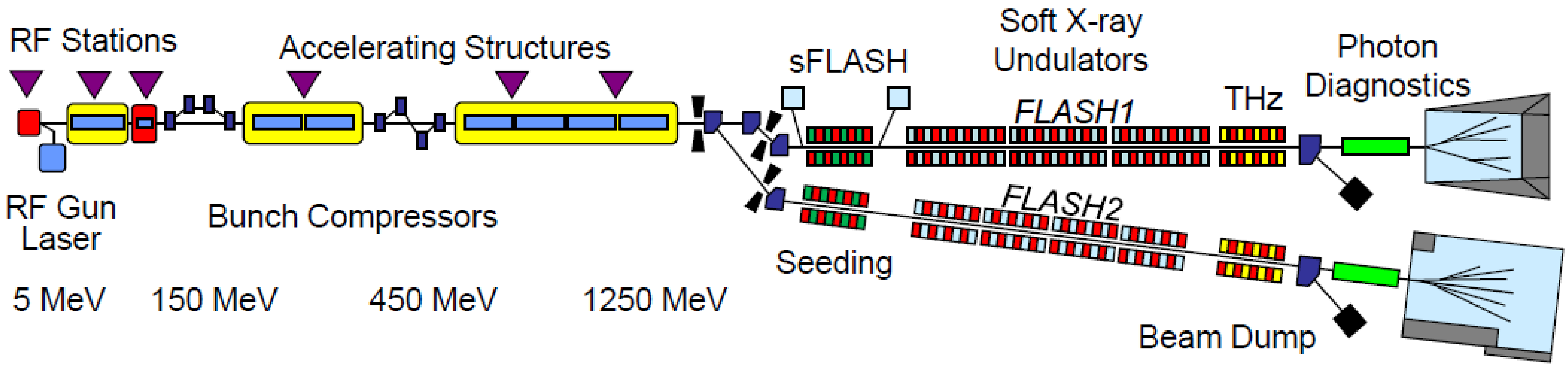


Goals: to see atomic details of viruses, make a film of chemical reactions or study matter under extreme conditions.

Free Electron Laser in Hamburg - FLASH

PITZ Photo Injector Test Facility Zeuthen

High brightness electron beams are served for the production of high intensity, high brightness light.



To produce such light with defined properties **detailed knowledge** of the electron beam parameters is needed.

Electron bunch characterization

Characteristic	Dimension	Origin	Diagnostic
Bunch charge	C, nC	Electron source	Faraday cup, integrating current transformer, …
Bunch energy	J, eV, MeV, GeV	Acceleration (RF fields)	Magnet spectrometer, …
Bunch transverse size	m, mm, μm	Emittance, transverse phase space (electron source, beam optics)	Screen station, wire scanner, …
Bunch length	m, mm, μm s, ps, fs	Energy spread, longitudinal phase space (electron source, acceleration, compression)	Streak camera, **transverse deflecting structure, tomography technique**, …
Bunch transverse position	m, mm, μm	Beam optics	Beam position monitor, screen station, …

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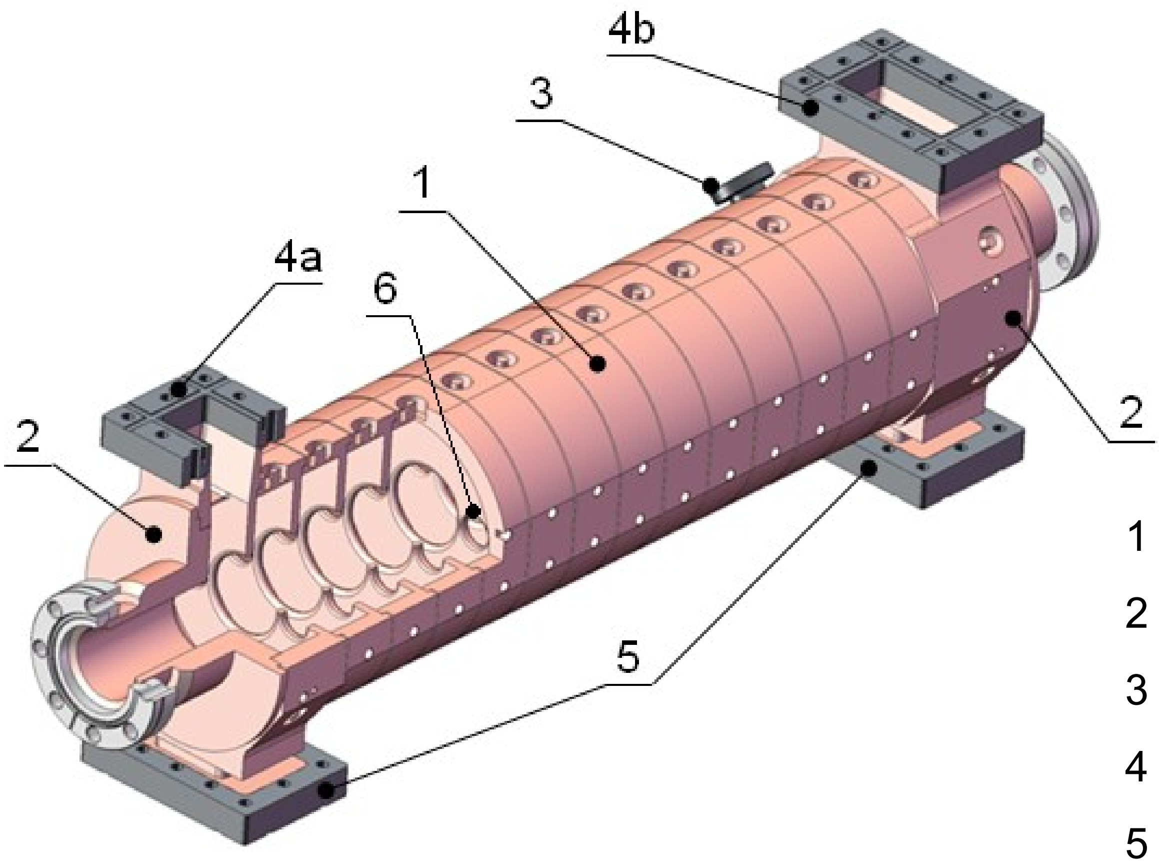
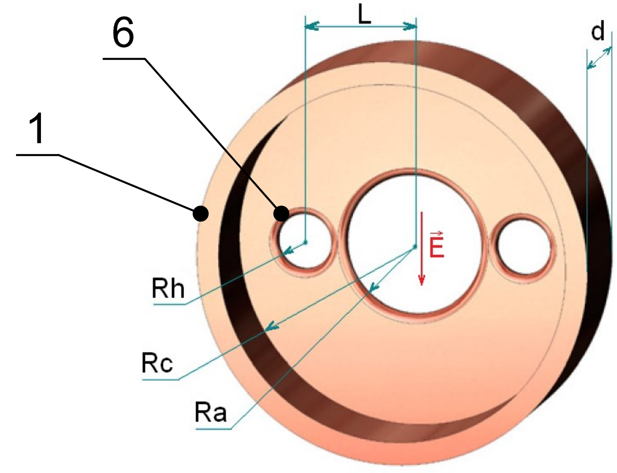
TDS for PITZ, 3D model





1 regular cell (14),

2 RF input and output coupler cells,

3 RF probe,

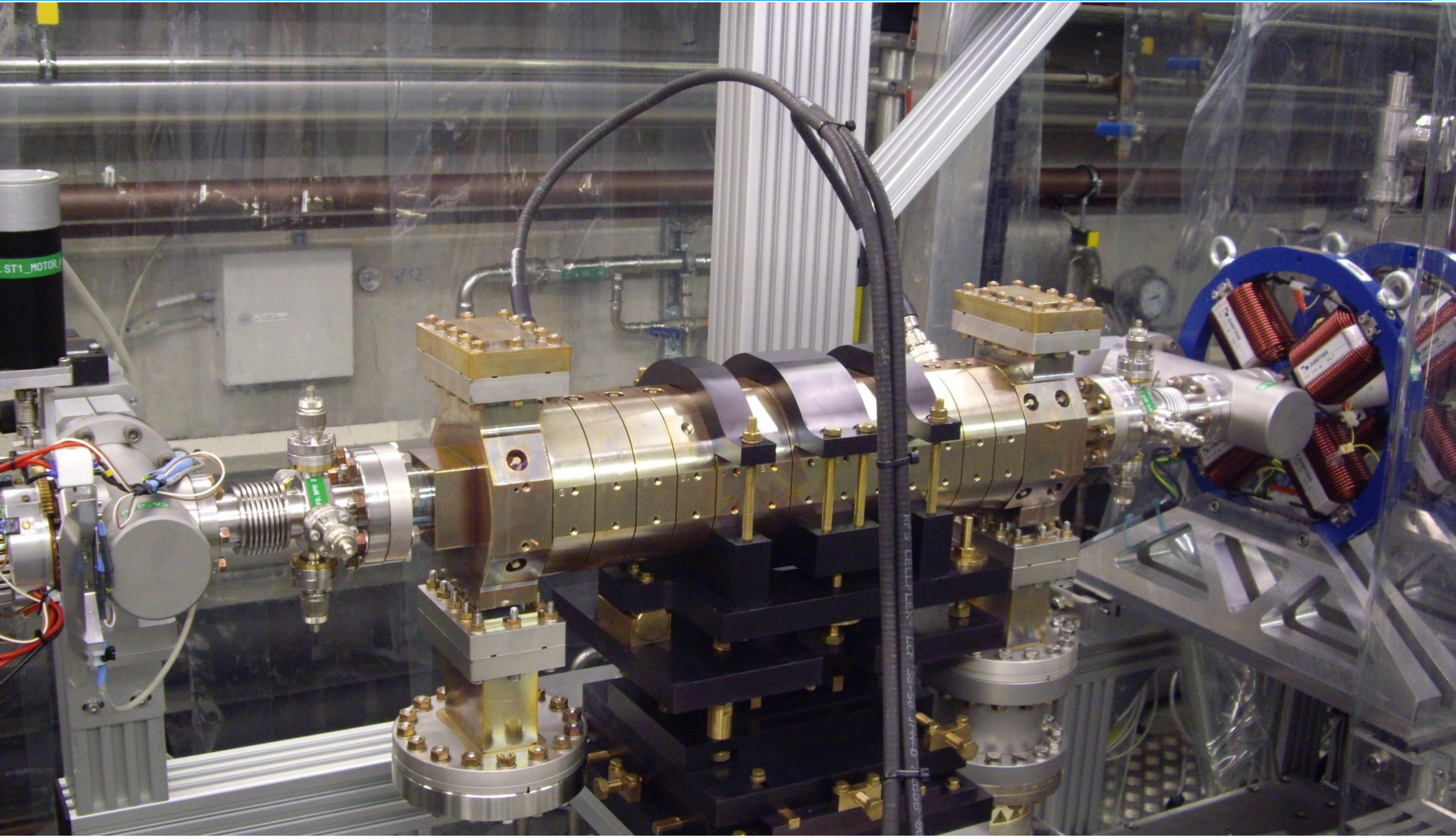
4 RF input and RF output flanges,

5 RF flanges for vacuum pumps,

6 coupling/stabilizing holes.

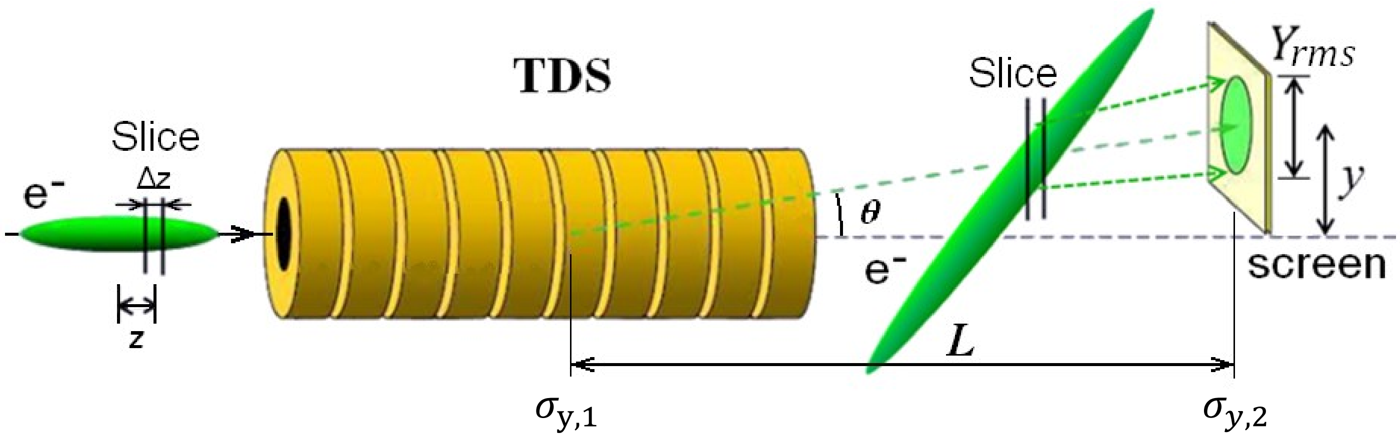
Designed and produced by INR, Troitsk, Russia.

TDS installed at PITZ



TDS basic principle

The structure deflects the electrons of the bunch vertically in linear dependence on their longitudinal coordinates within the bunch.



z – slice longitudinal position
θ – deflection angle,
L – drift length between TDS and screen,
p – beam momentum,
V_0 – deflecting voltage,
k – wave number ($k = \frac{\omega}{c}$),
$\sigma_{y,1}$ – vertical beam size in the TDS
$\sigma_{y,2}$ – vertical beam size on the screen
Y_{rms} – slice vertical rms size

$$y = \tan(\theta) \cdot L = \frac{\Delta p_\perp}{p} \cdot L = \frac{eV_0 k}{pc} z \cdot L,$$

TDS shear parameter $S = \frac{eV_0 k}{pc} L,$

resolution length: $\delta z = \frac{\sigma_{y,2}}{S},$

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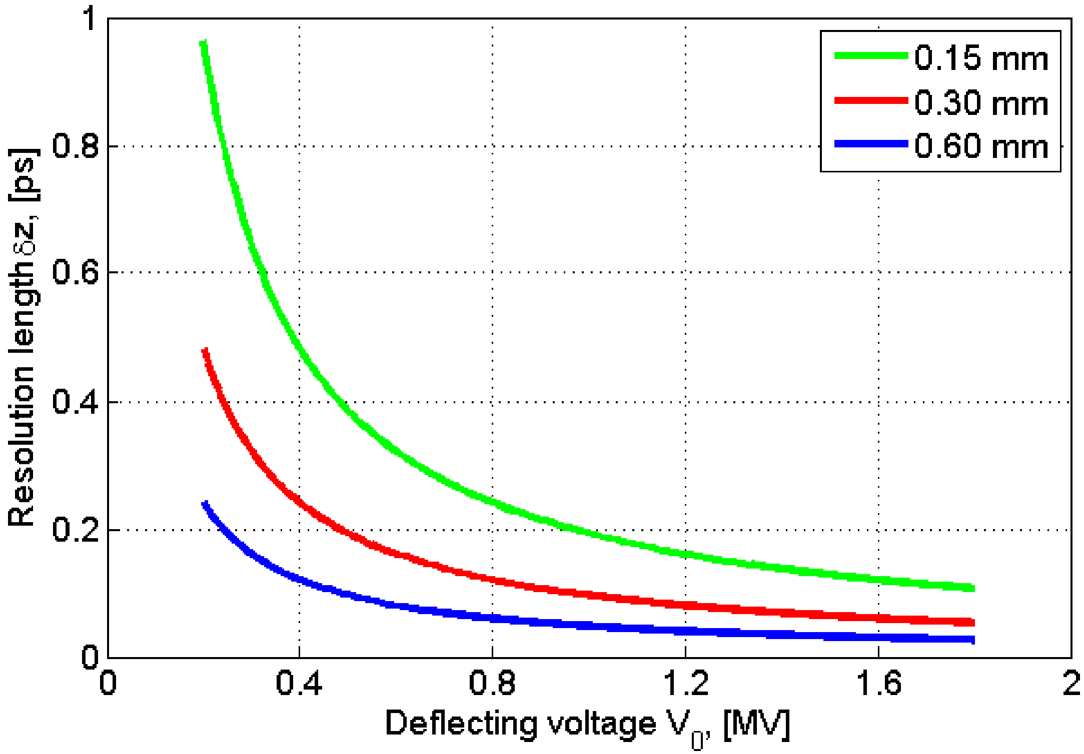
Resolution length

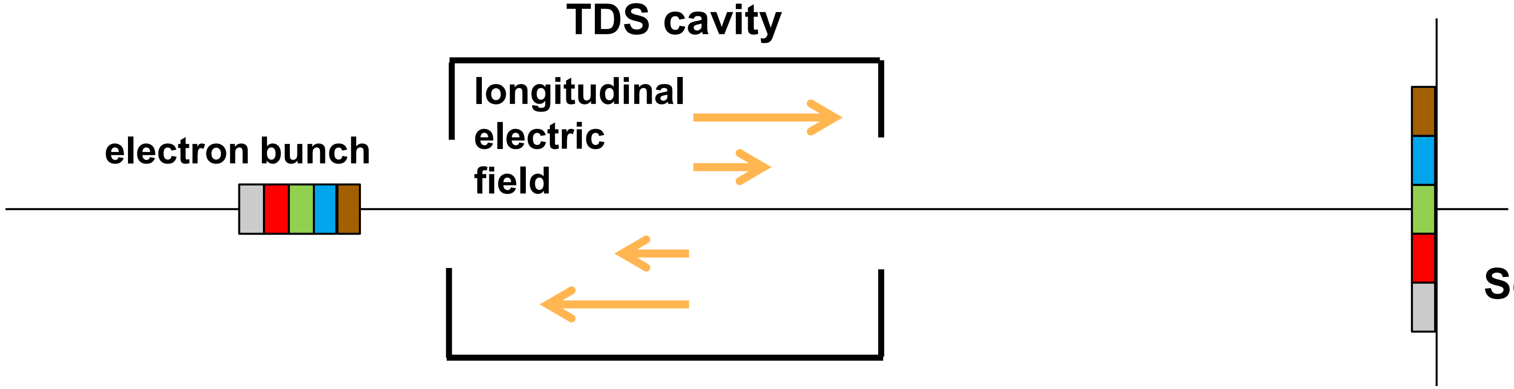
$$S = \frac{\sigma_{y,1} \cdot \sigma_{y,2}}{\varepsilon_y} \cdot \sin(\Delta\psi_y) \cdot \frac{eV_0 k}{pc}, \qquad \delta z = \frac{\sigma_{y,2}}{S} = \frac{\varepsilon_y}{\sigma_{y,1} \cdot \sin(\Delta\psi_y)} \cdot \frac{pc}{eV_0 k}.$$

$\Delta\psi_y$ – betatron phase advance, ε_y – vertical geometrical transverse emittance.

Resolution length for three vertical beam sizes $\sigma_{y,1}$ in the TDS



Induced momentum spread

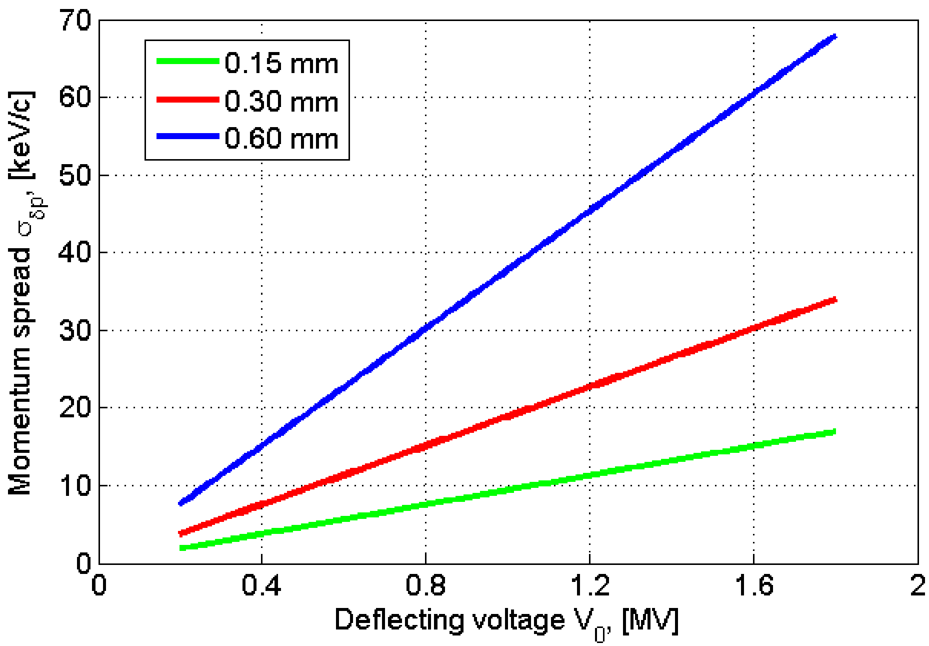


Panofsky-Wenzel theorem:

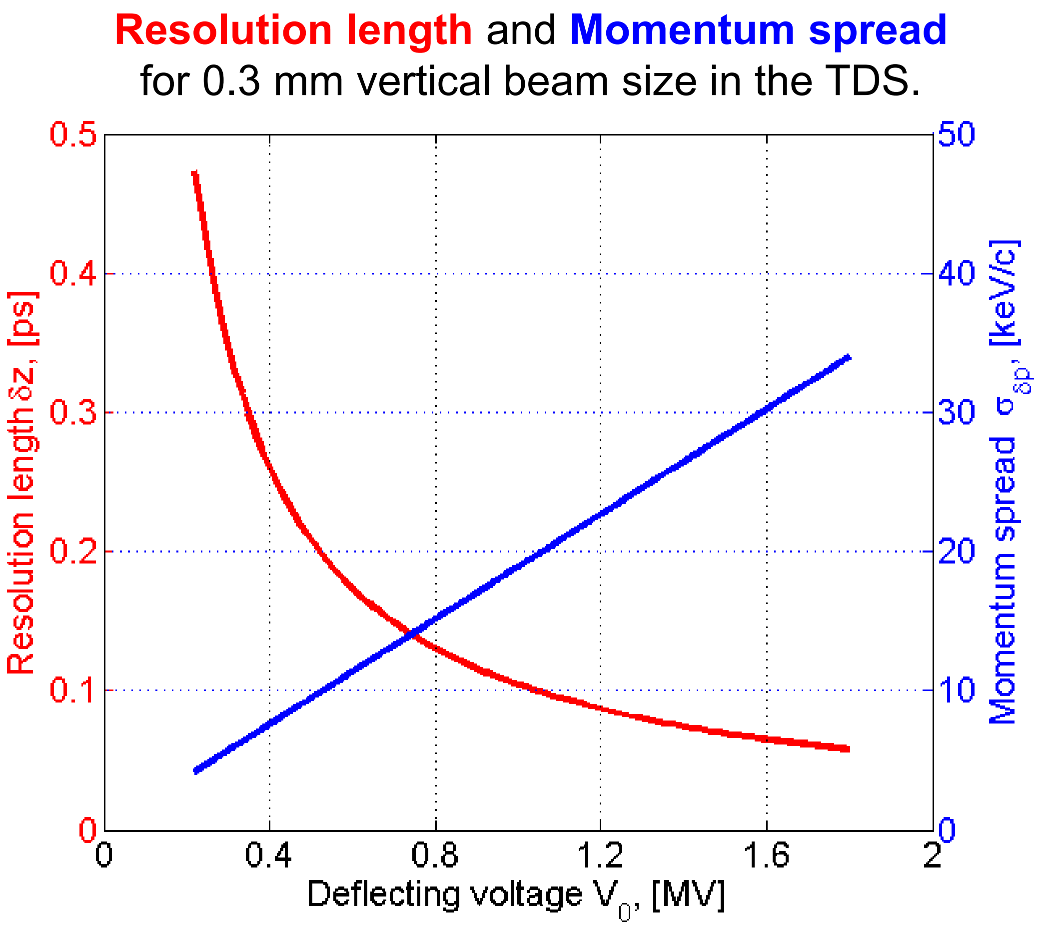
Transverse deflection is only possible if a transverse gradient of the longitudinal field is present.

$$\sigma_{\delta p} = \frac{eV_0 k}{p_0 c} \cdot \sigma_{y,1}$$

Momentum spread for three vertical beam sizes σ in the TDS



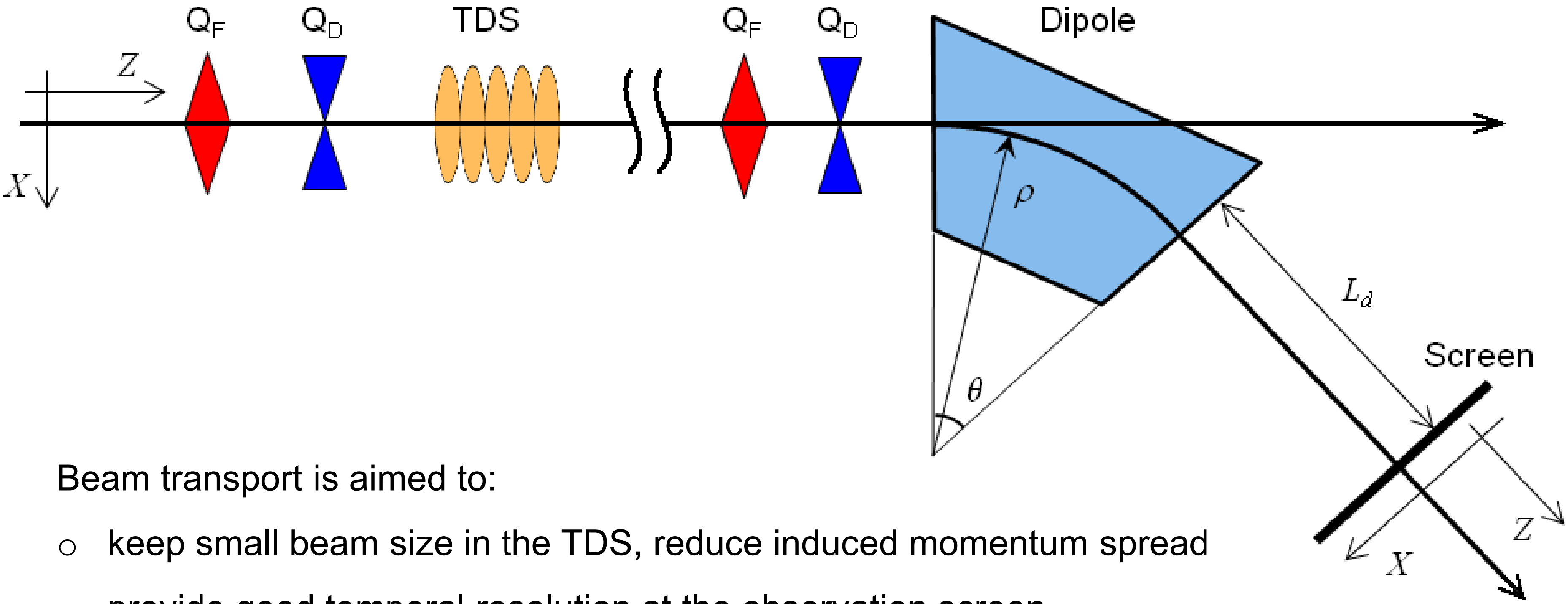
Resolution compromise



Higher deflecting voltage gives better (smaller) resolution length, but also gives higher induced momentum spread.

Higher vertical beam size in the TDS gives better (smaller) resolution length, but gives higher induced momentum spread as well.

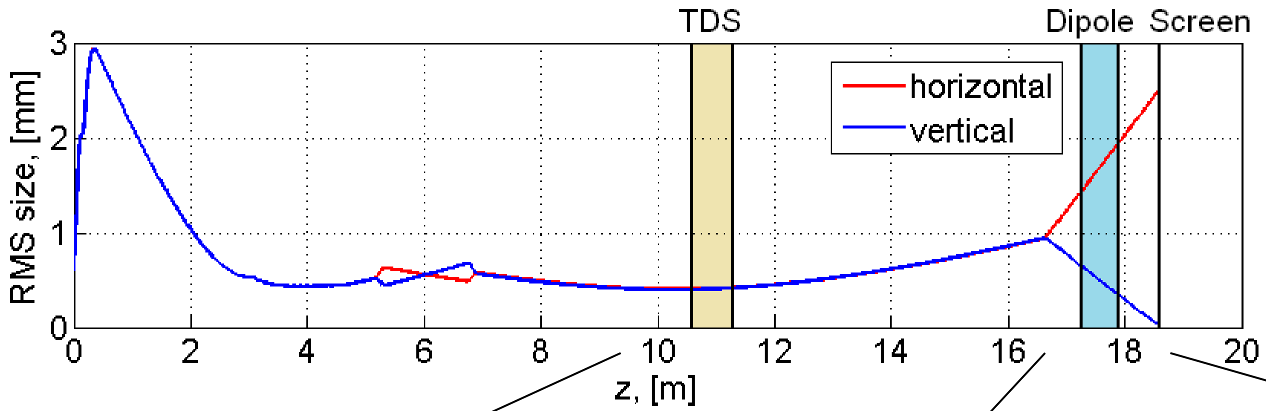
Longitudinal phase space measurements with TDS



Beam transport is aimed to:

- keep small beam size in the TDS, reduce induced momentum spread
- provide good temporal resolution at the observation screen,
- provide good momentum resolution.

Numerical simulation of measurements

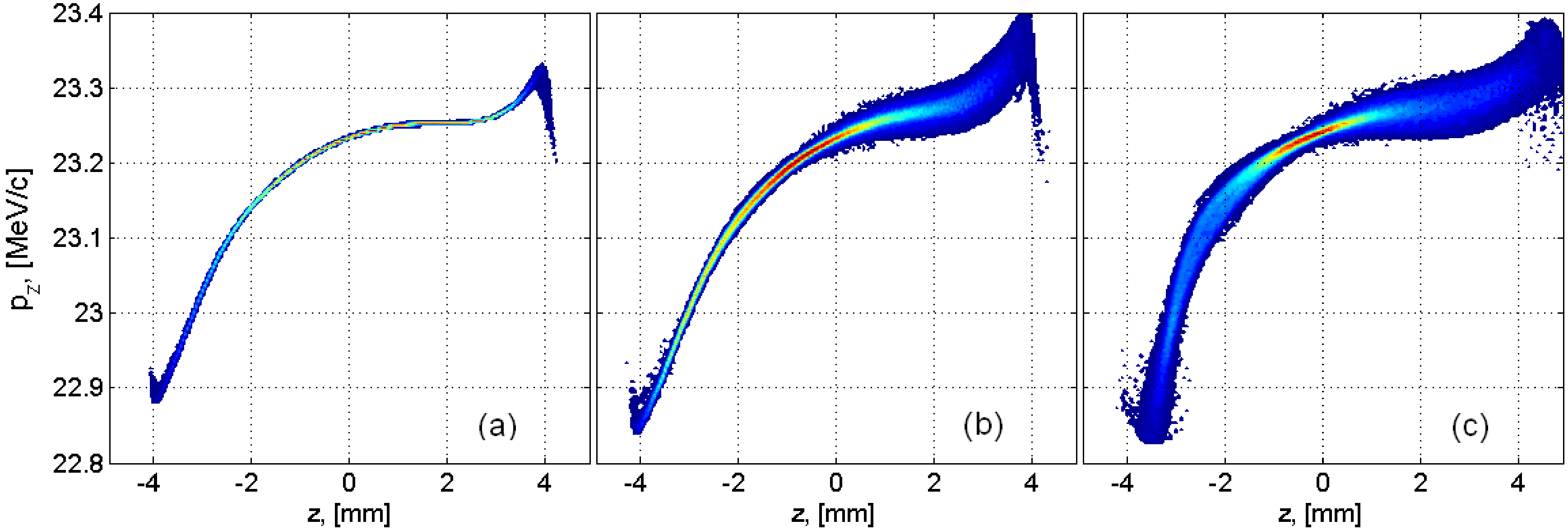


beam is focused vertically and defocused horizontally on the observation screen

In the front of the TDS

In the front of the dipole

Reconstructed phase space



TDS summary

+ Powerful diagnostic tool for various types of measurements:
  - bunch temporal profile (current distribution)
  - transverse slice emittance
  - longitudinal phase space

+ Direct, single shot measurements

− Expensive and complicated in realization

- > 1. Motivation
- > 2. Transverse deflecting structure
- > **3. Longitudinal phase space tomography**
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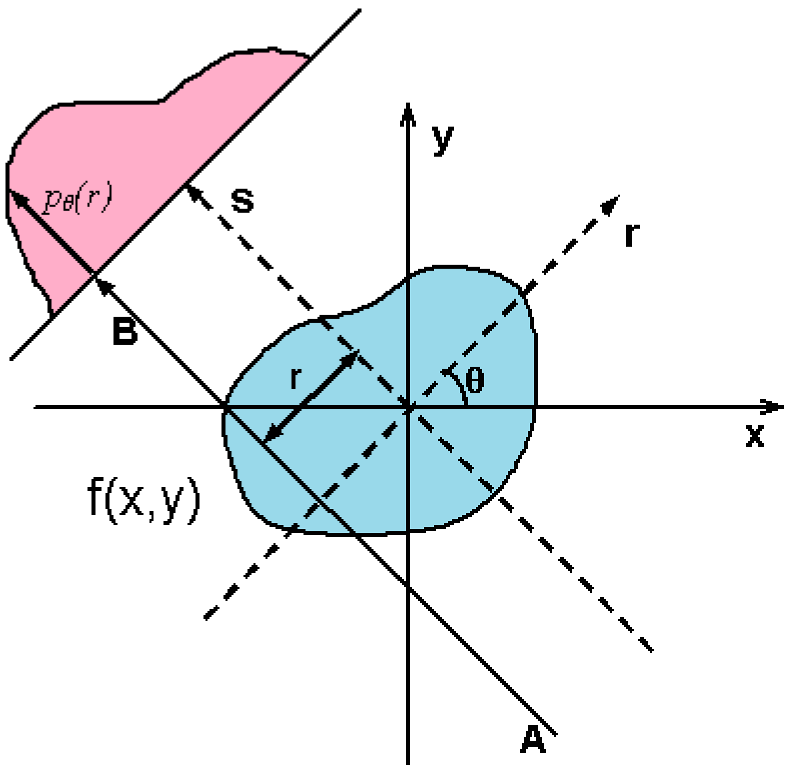
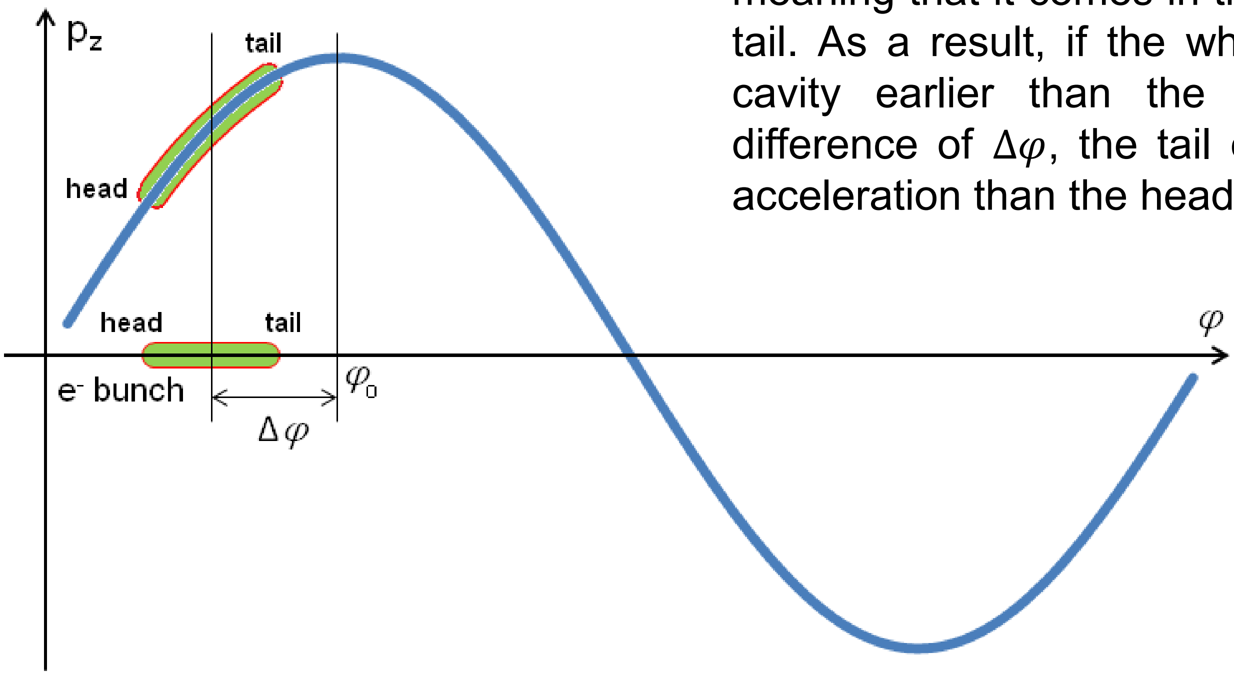
Tomographic reconstruction method



- For the unknown object $f(x, y)$ one can measure projection of this object $p_\theta(r)$ at different angles θ.
- Resulted projections $p_\theta(r)$ are called tomography transformation of the object $f(x, y)$.
- Procedure to restore unknown object from the set of projections is called tomographic reconstruction. Possible algorithms are **ART**, **MENT** …
- This procedures can be applied to the longitudinal phase space.

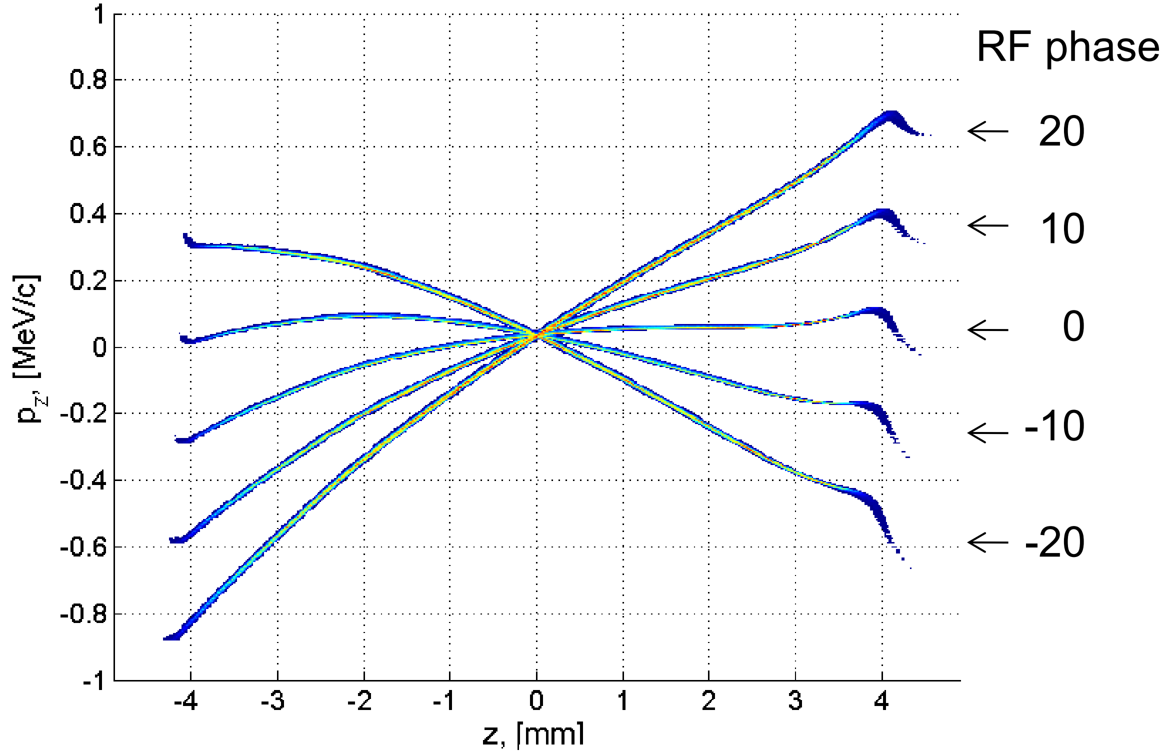
Particle acceleration in an RF cavity



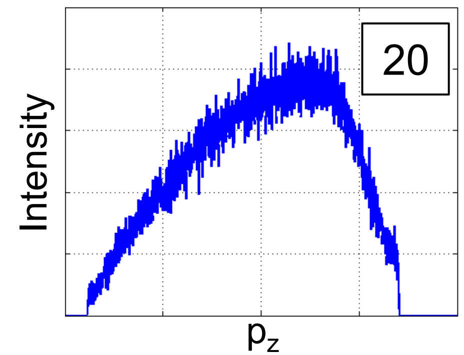
The head of the bunch is coming first to the cavity meaning that it comes in the earlier RF phase than the tail. As a result, if the whole bunch is coming to the cavity earlier than the phase φ_0 with a phase difference of $\Delta\varphi$, the tail of the bunch will get higher acceleration than the head.

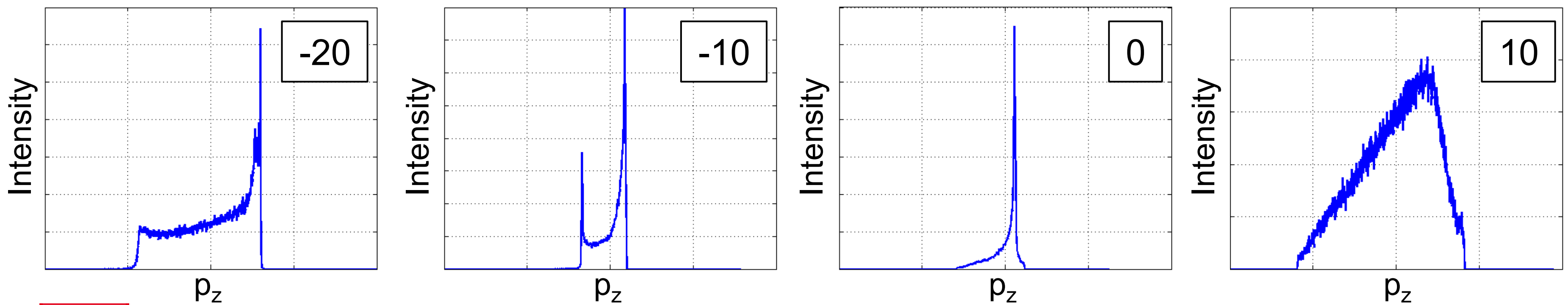
$p_z = p_0 + V \cdot cos(\varphi - \varphi_0)$, momentum slope (or chirp) $k = -\frac{dp_z}{dt} = V\omega \cdot sin(\Delta\varphi)$

Simulated longitudinal phase spaces, 1 nC charge



Simulated electron bunch longitudinal phase spaces for 5 booster RF phases: -20, -10, 0, 10 and 20.





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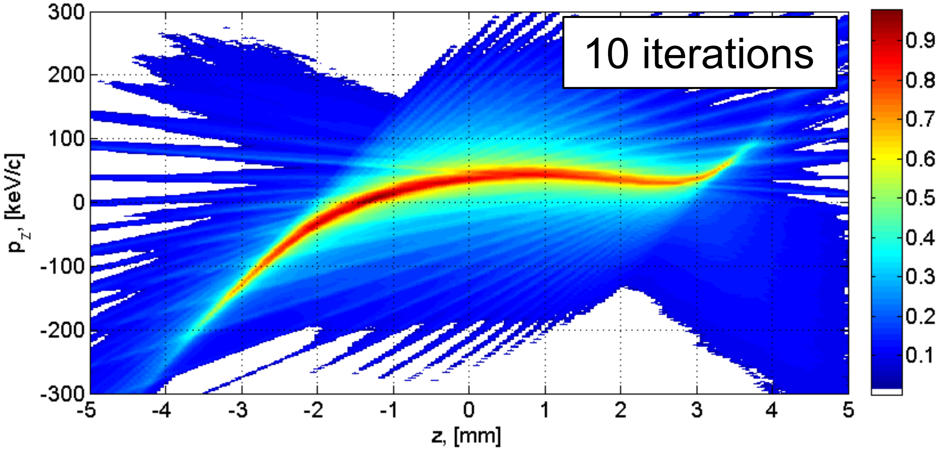
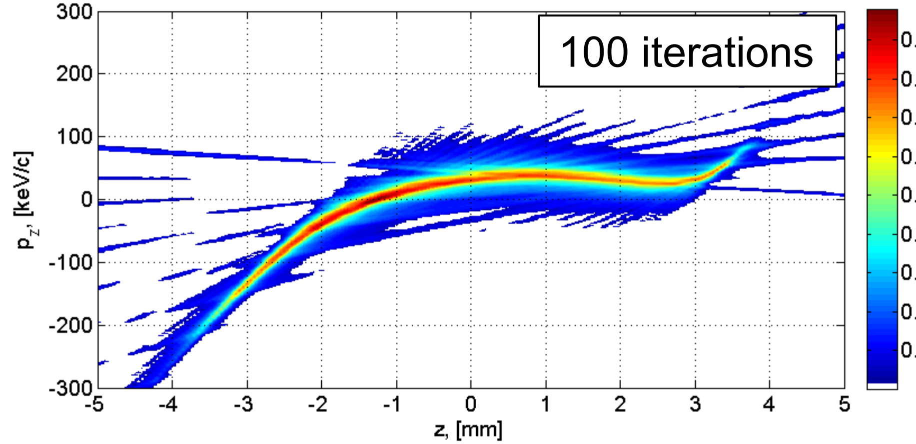
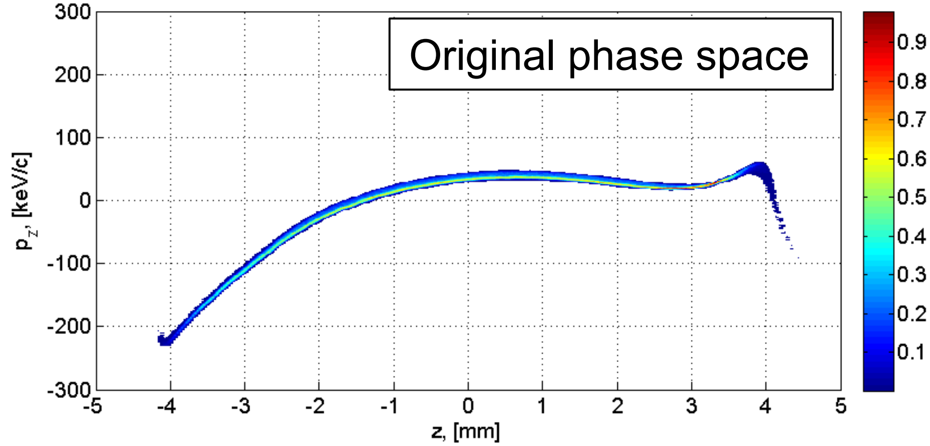
Result of ART reconstruction from the simulated data





4 keV/c momentum binning,
RF phase from -20 to +20
with step of 1 degree,
41 total projections



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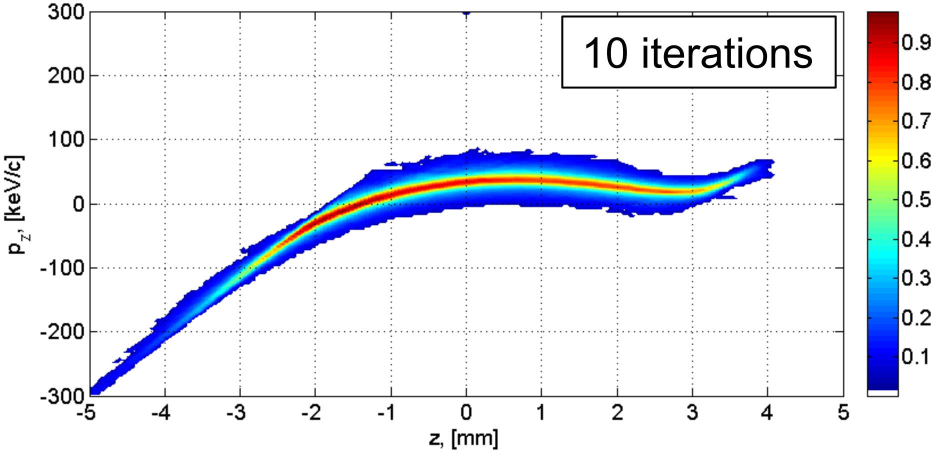
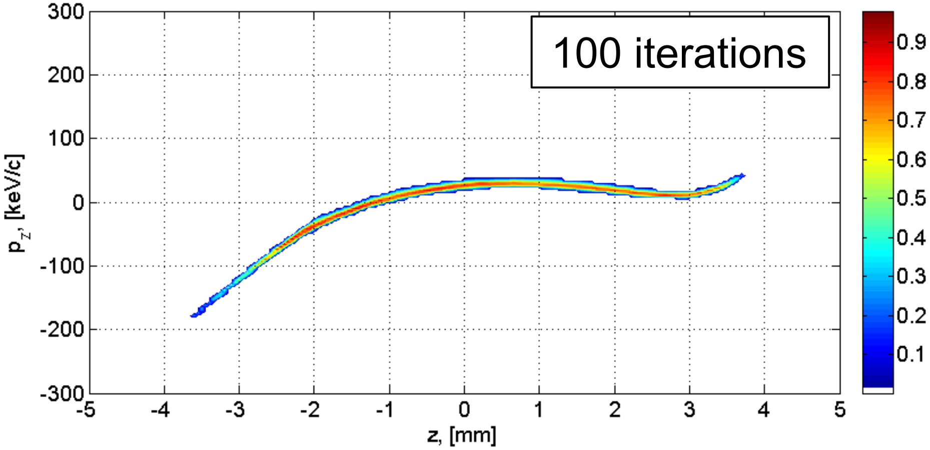
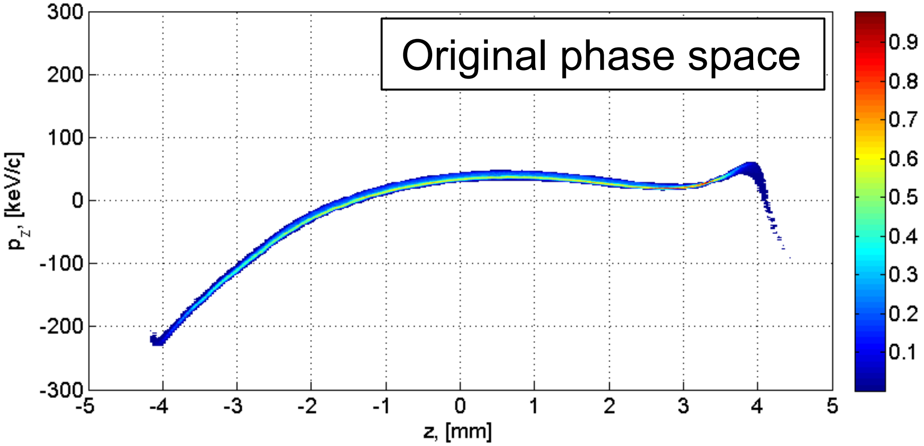
Result of ART reconstruction from the simulated data







4 keV/c momentum binning,
RF phase from -15 to +15
with step of 0.2 degree,
151 total projections

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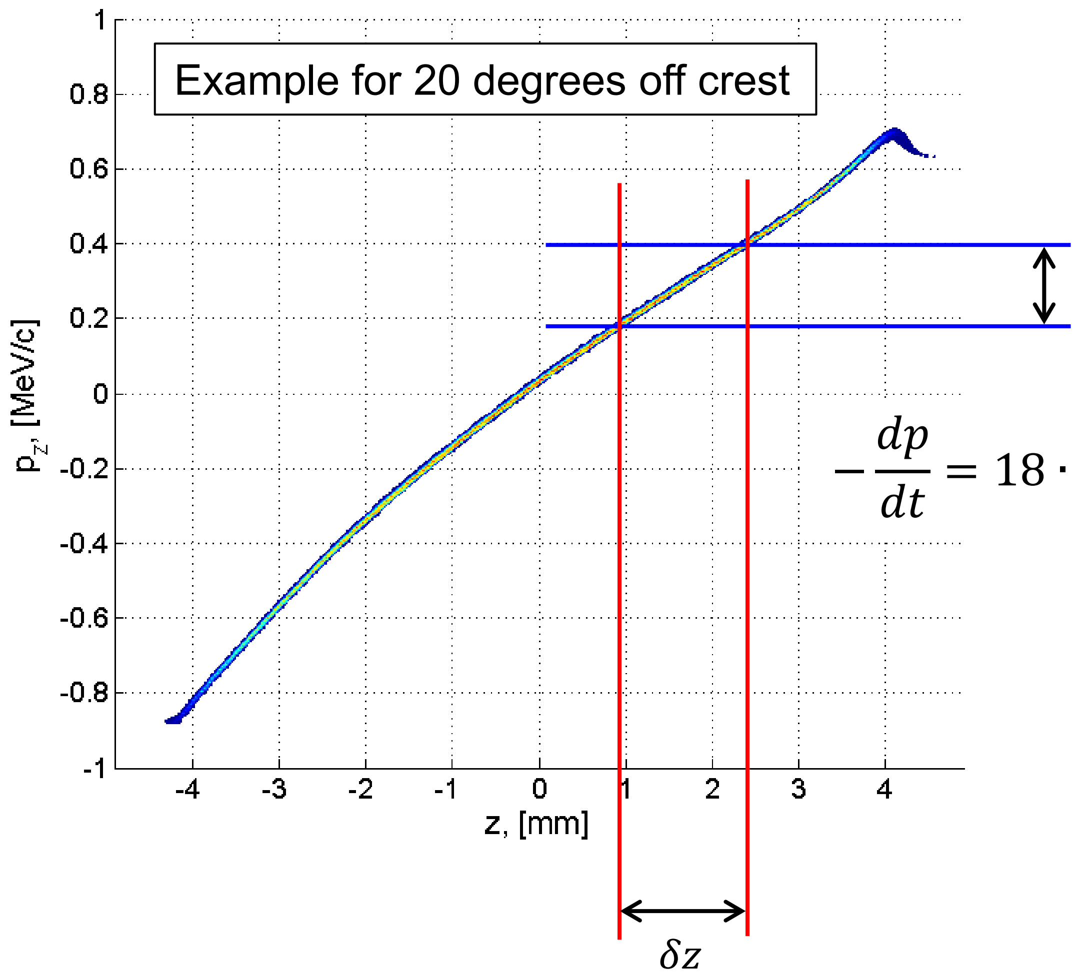
Estimation of longitudinal resolution



For the simulation close to the PITZ conditions:

$$p_z = 6.7MeV/c + 18MeV/c \cdot cos(\varphi)$$

slope $k = -\frac{dp_z}{dt}$

$$-\frac{dp}{dt} = 18 \cdot 2\pi f \cdot \sin(\varphi) = +147 \frac{keV/c}{ps} \cdot \sin(\varphi)$$

$$k = -\frac{dp}{dt} = 50 \frac{keV/c}{ps}$$

$$\delta z = \frac{\delta p}{k}$$

From the **rough estimation**, for $\delta p = 5\ keV/c \rightarrow \delta z = 0.1\ ps = 30\ \mu m$

Tomographic reconstruction summary

+ Diagnostic technique for longitudinal phase space measurements:

  bunch temporal profile (current distribution)

+ No additional hardware required (just dispersive section for momentum distribution measurements)

− Multi shot measurements

− Not direct

− Sophisticated data treatment

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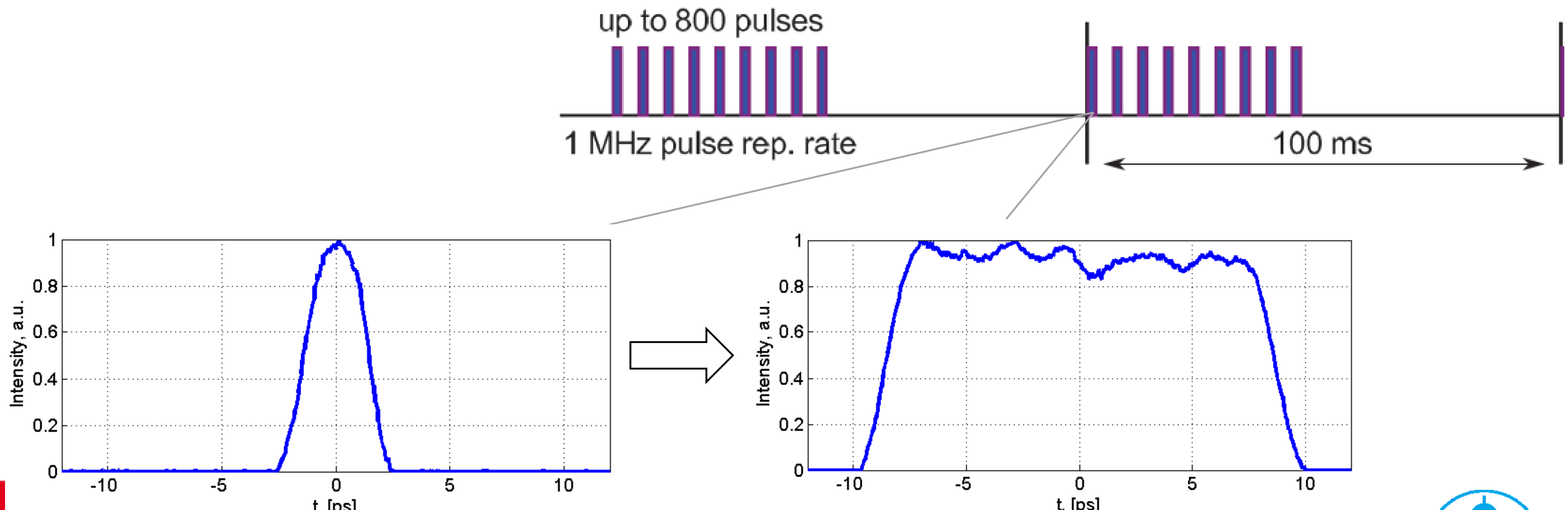
PITZ parameters and laser pulse structure

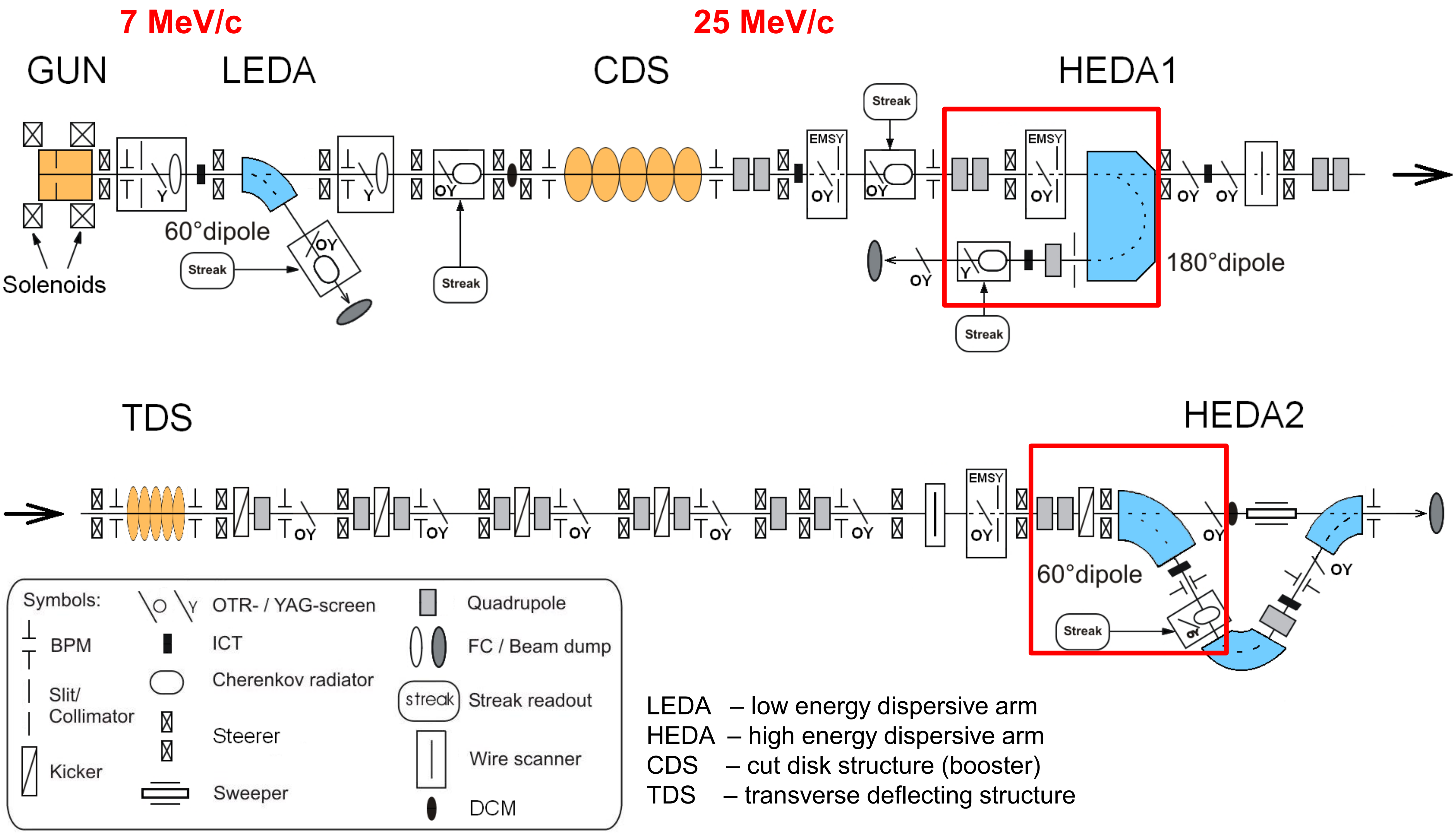
PITZ photo injector main parameters:

Bunch charge	0 … 4 nC
Repetition rate	10 Hz
Beam momentum after gun	0 … 7 MeV/c
Beam momentum after booster	0 … 25 MeV/c
Number of bunches	1 … 800
Laser pulse temporal shape	2 ps Gauss … 22 ps flat-top

Laser pulse train structure:



The Photo Injector Test facility, Zeuthen site (PITZ)



LEDA – low energy dispersive arm
HEDA – high energy dispersive arm
CDS – cut disk structure (booster)
TDS – transverse deflecting structure

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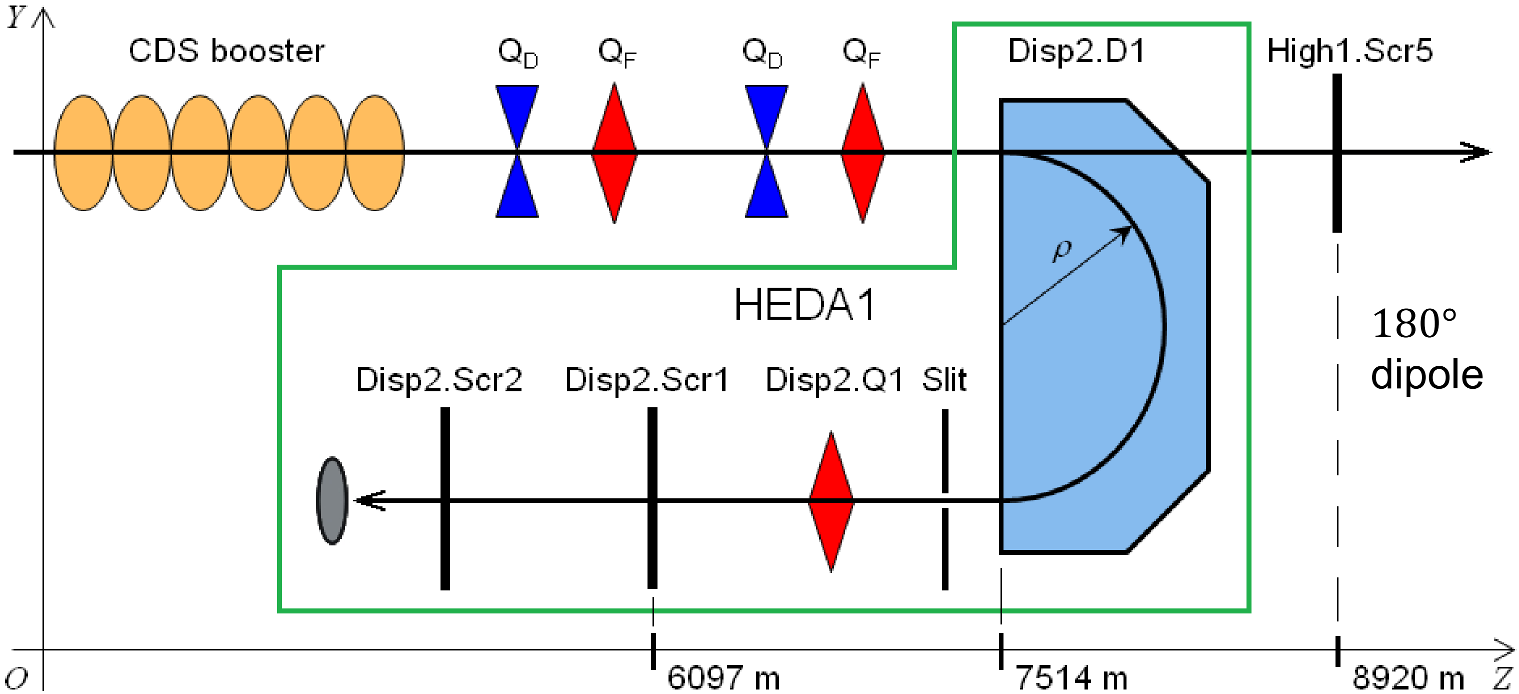
HEDA1 momentum measurements

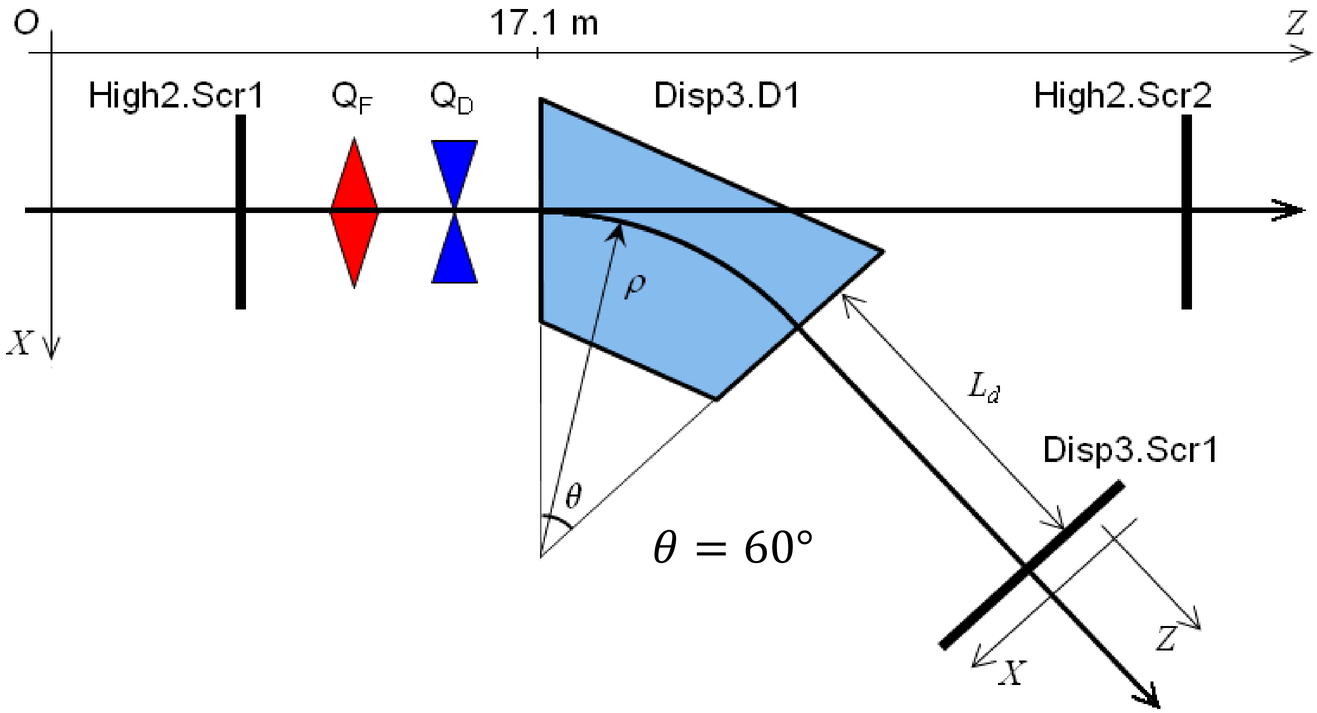


Dispersion $D_y = \rho(1 - cos(\theta)) + L_d sin(\theta) = 2\rho$ = 0.6 m

Beam size on screen $\sigma_x = D_x \frac{\Delta p}{p}$

1 camera pixel => 110 µm → $\frac{\Delta p}{p}$ = 1.8·10^{-4} → 4.0 keV/c

HEDA2 momentum measurements



Dispersion $D_x = \rho(1 - cos(\theta)) + L_d sin(\theta)$ = 0.9 m

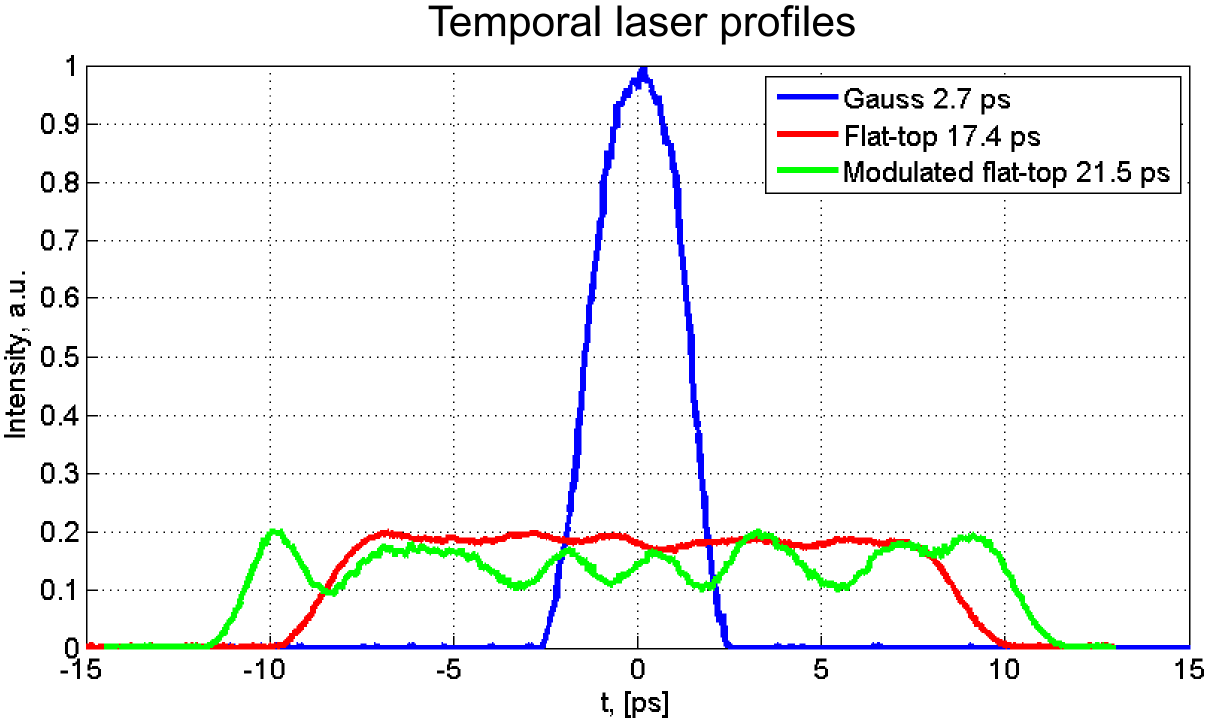
Beam size on screen $\sigma_x = D_x \frac{\Delta p}{p}$

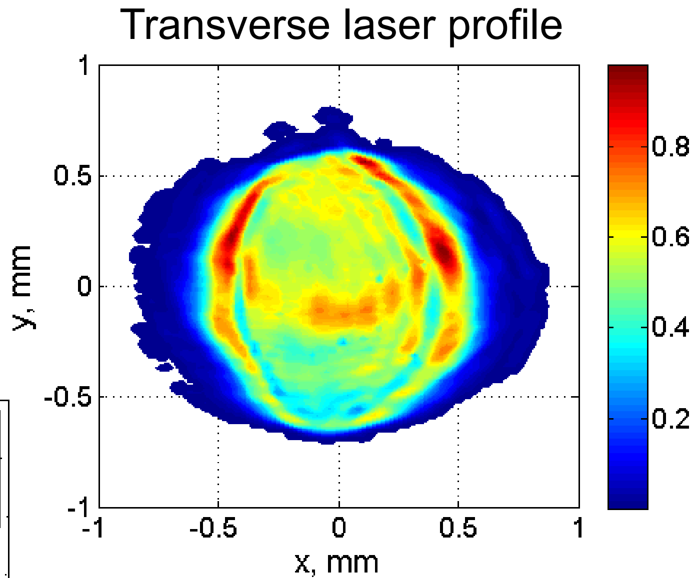
1 camera pixel => 64 µm → $\frac{\Delta p}{p}$ = 7.1·10^{-5} → 1.5 keV/c

Laser profiles used for the measurements

For the measurements 3 temporal profile were used.

Laser intensity was adjusted accordingly to produce required bunch charge.



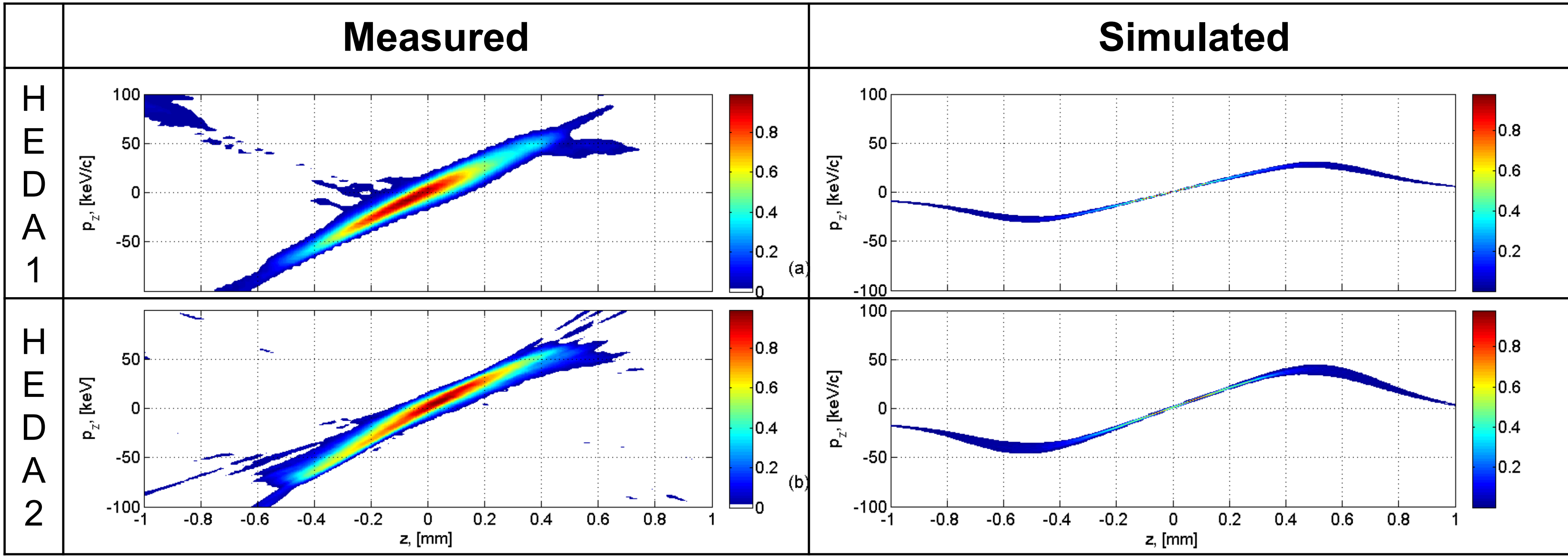


x RMS = 0.36 mm
y RMS = 0.37 mm

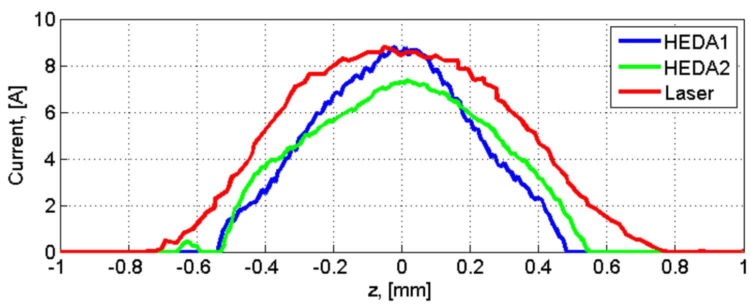
Profiles are normalized to have the same area.

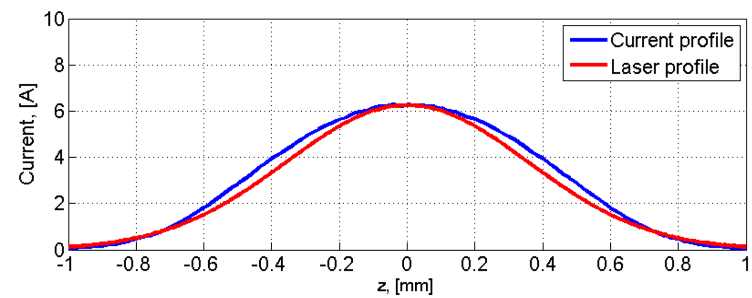
Laser Profile \ Bunch charge	20 pC	100 pC	700 pC	1 nC
Gauss, 2.7 ps	✓		✓	
Flat-top, 17.4 ps	✓	✓		✓
Modulated, 21.5 ps	✓	✓		✓

Results for Gaussian laser pulse and 20 pC charge



Reconstructed phase spaces are much wider in momentum axis than expected from the simulations





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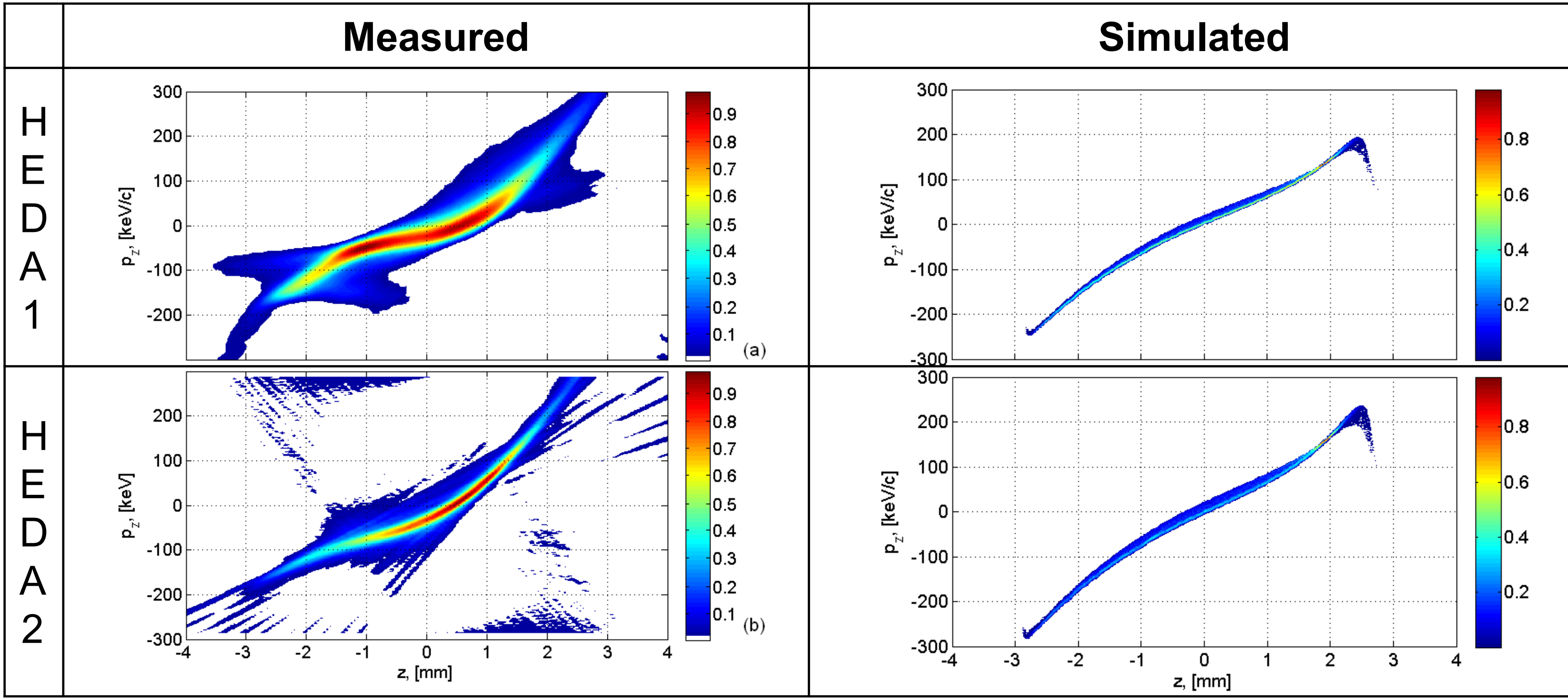
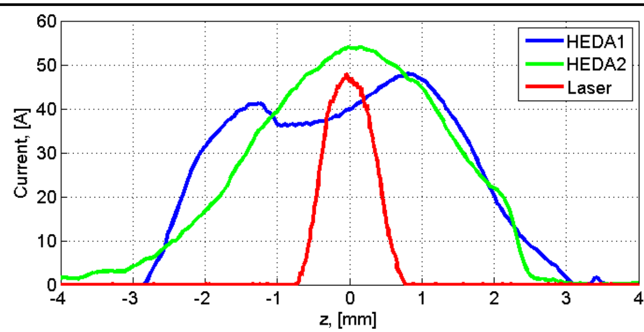
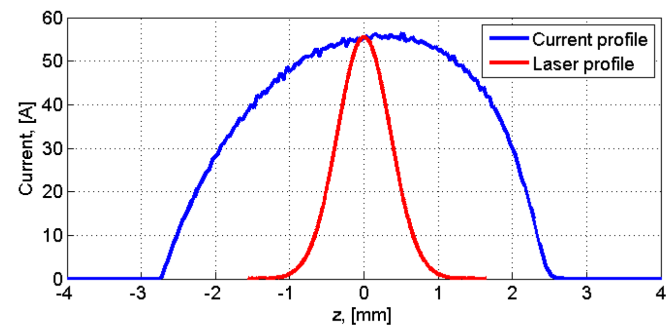
Results for Gaussian laser pulse and 700 pC charge







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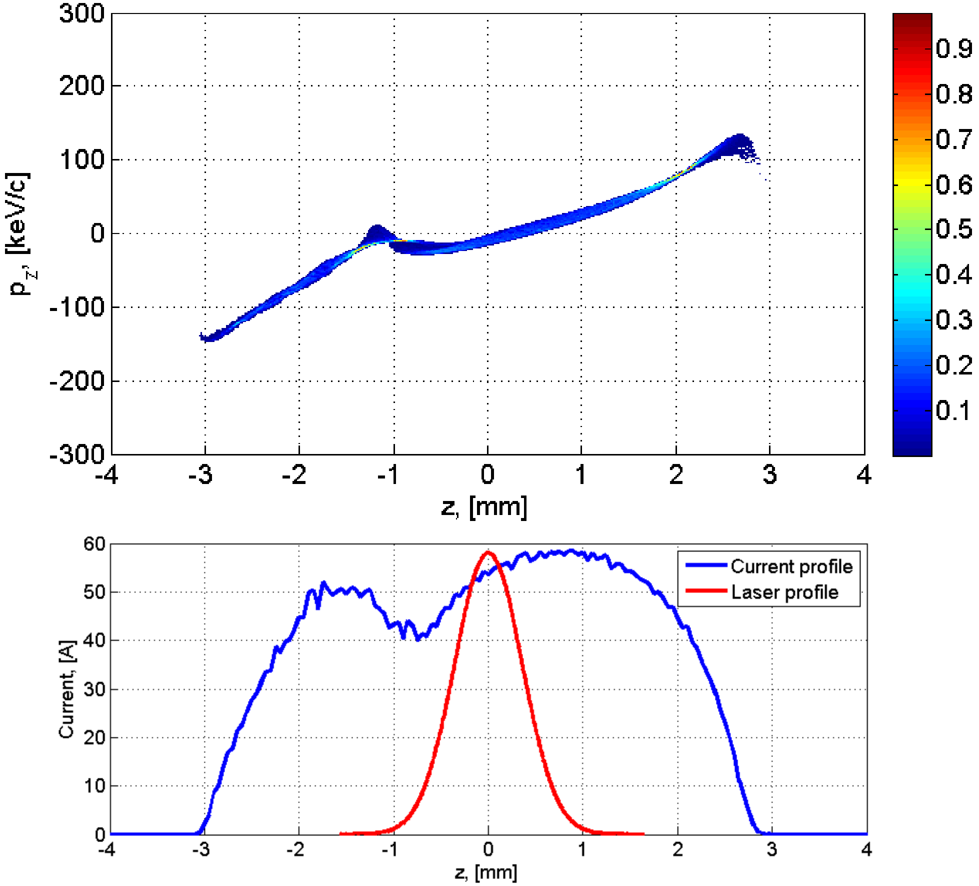
Simulation for Gaussian laser pulse and high charge

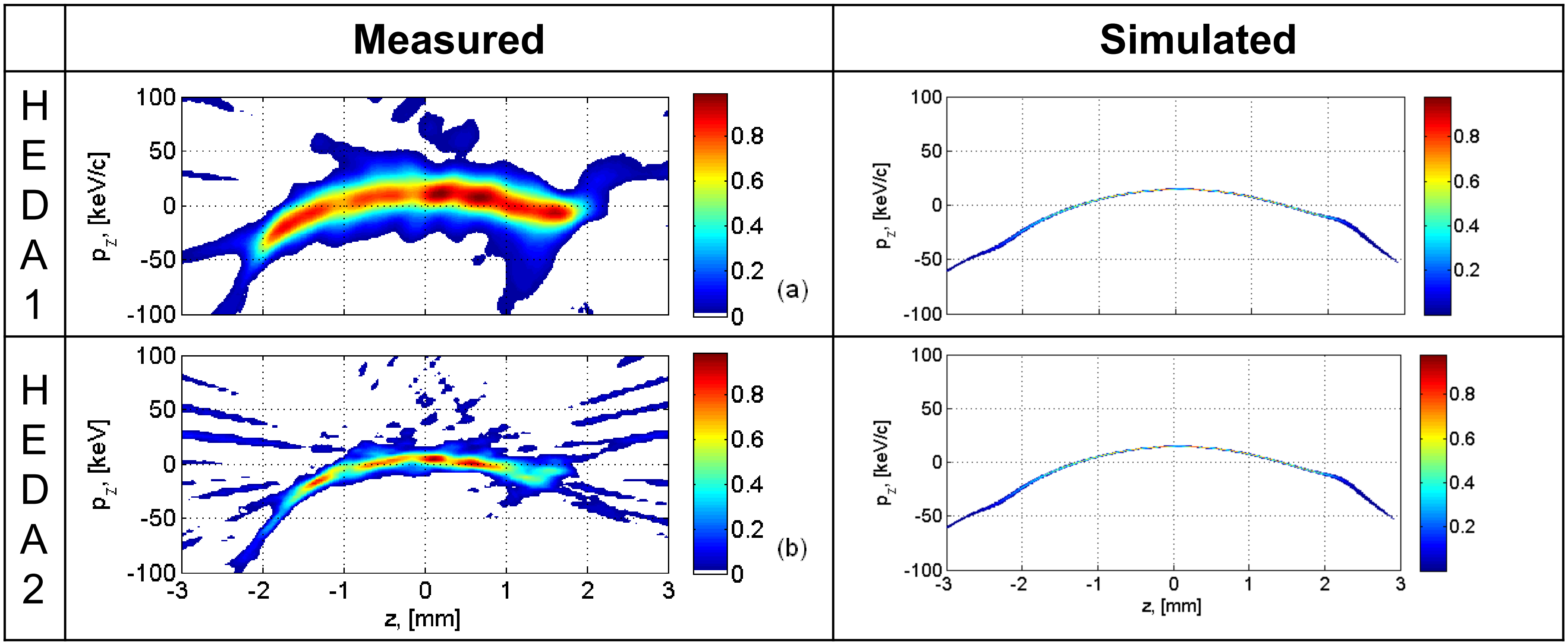


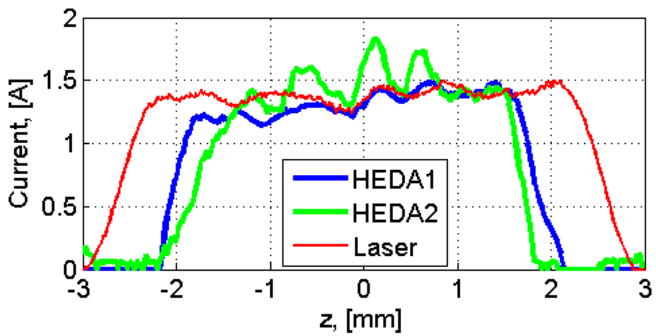
The laser was set to have **2 nC** in bunch, but extracted charge was about **0.8 nC**.

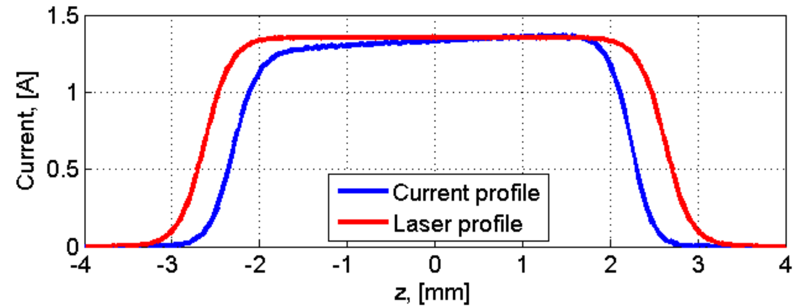
Resulted phase space and current profile are similar to ones observed in the measurements.

Laser Profile \ Bunch charge	20 pC	100 pC	700 pC	1 nC
Gauss, 2.7 ps	✓		✓	
Flat-top, 17.4 ps	✓	✓		✓
Modulated, 21.5 ps	✓	✓		✓

Results for Flat-top laser pulse and 20 pC charge

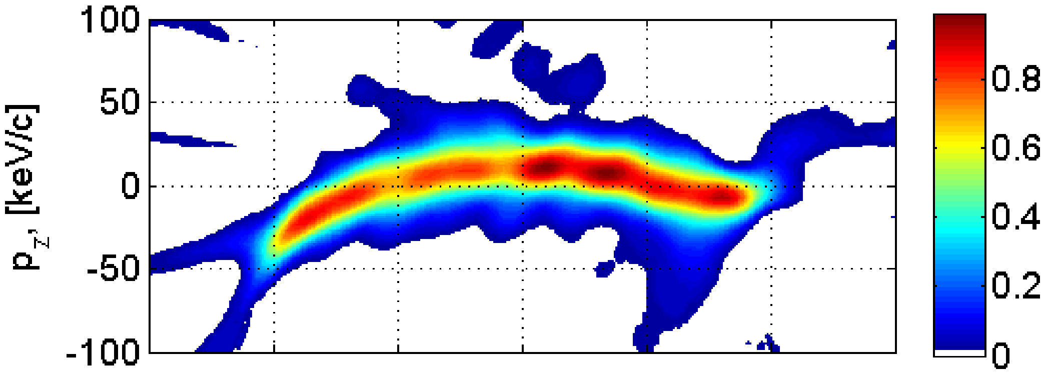




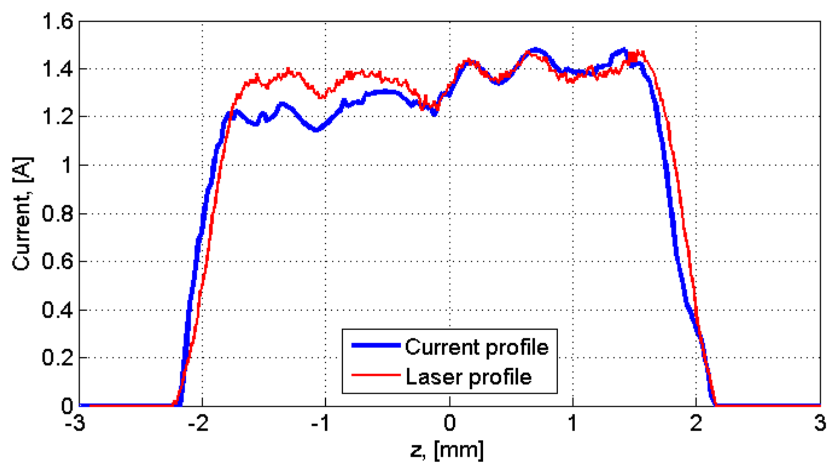


Current profile is in good agreement with the temporal laser profile.

Comparison of the current profile with laser

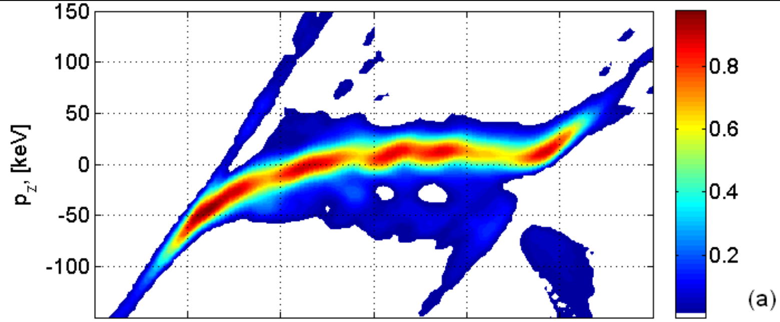
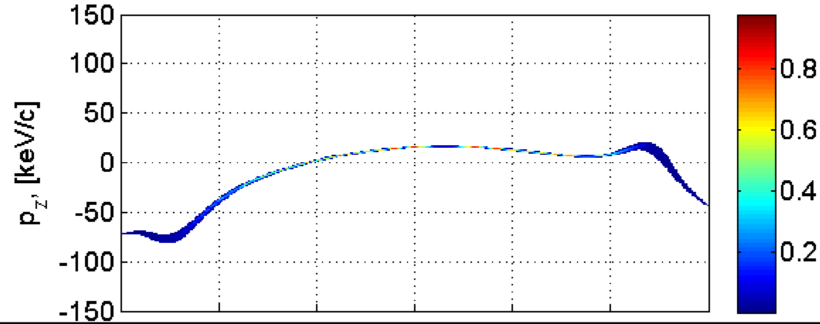
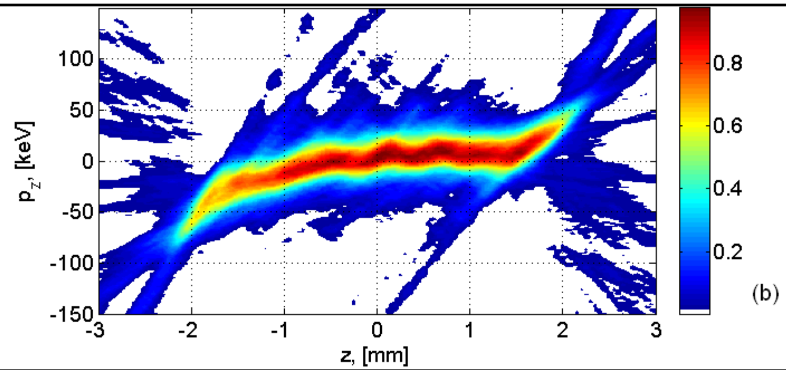
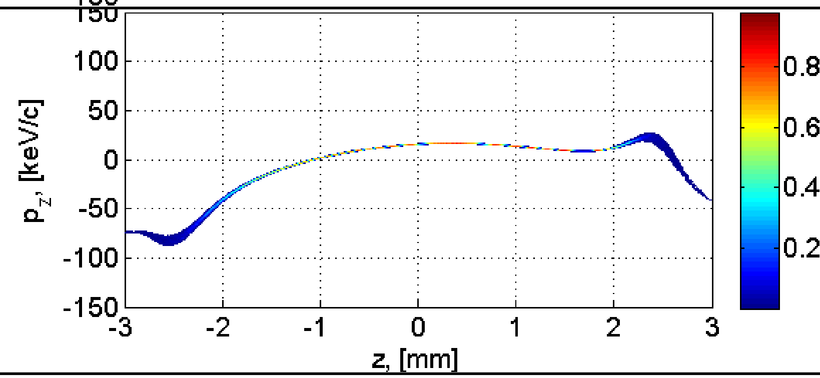


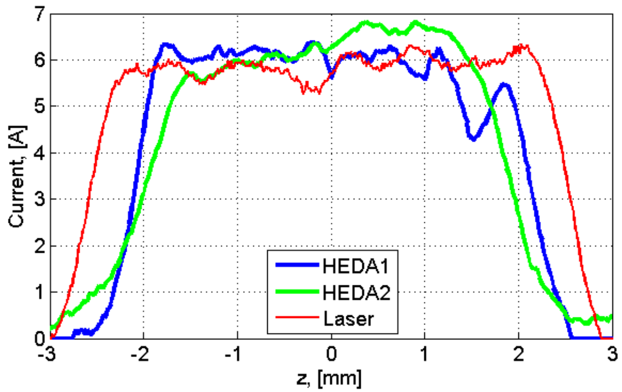
Phase space as well as current profile are in good agreement with the laser temporal profile.

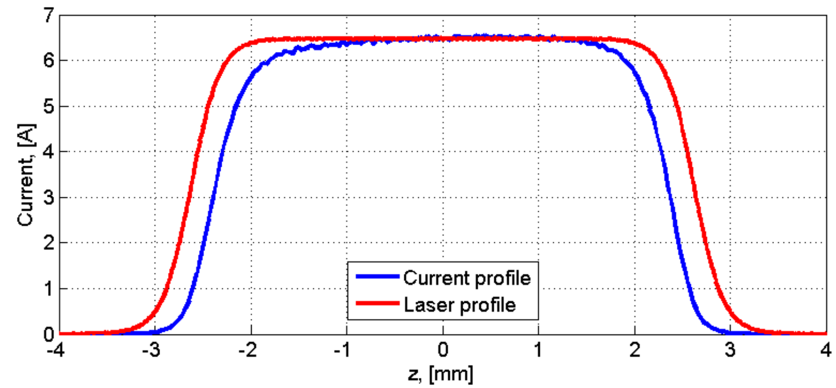


Temporal axis for the laser profile was scaled by 0.75 to better overlap the current profile.

Results for Flat-top laser pulse and 100 pC charge

	Measured	Simulated
HEDA1		
HEDA2		





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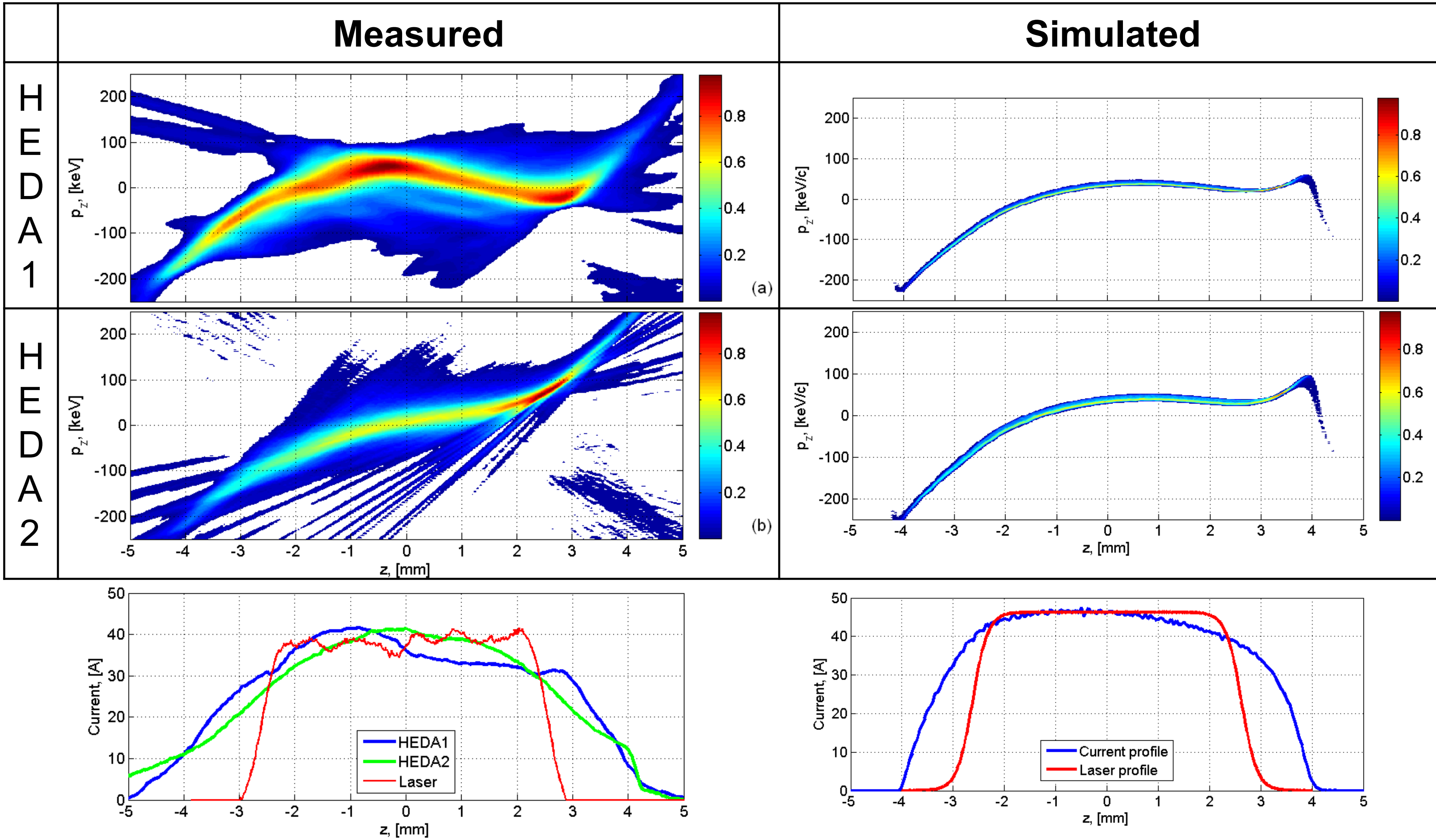
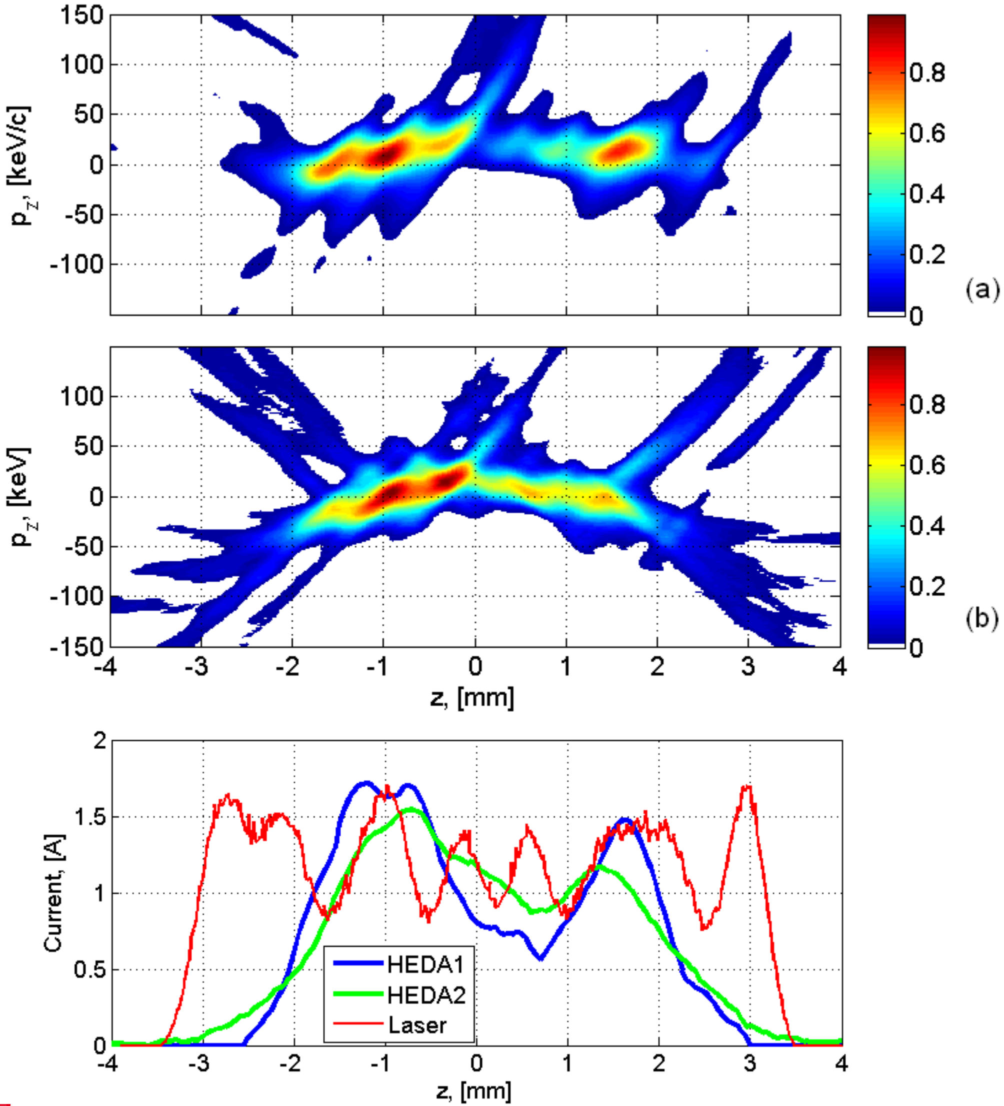
Results for Flat-top laser pulse and 1 nC charge



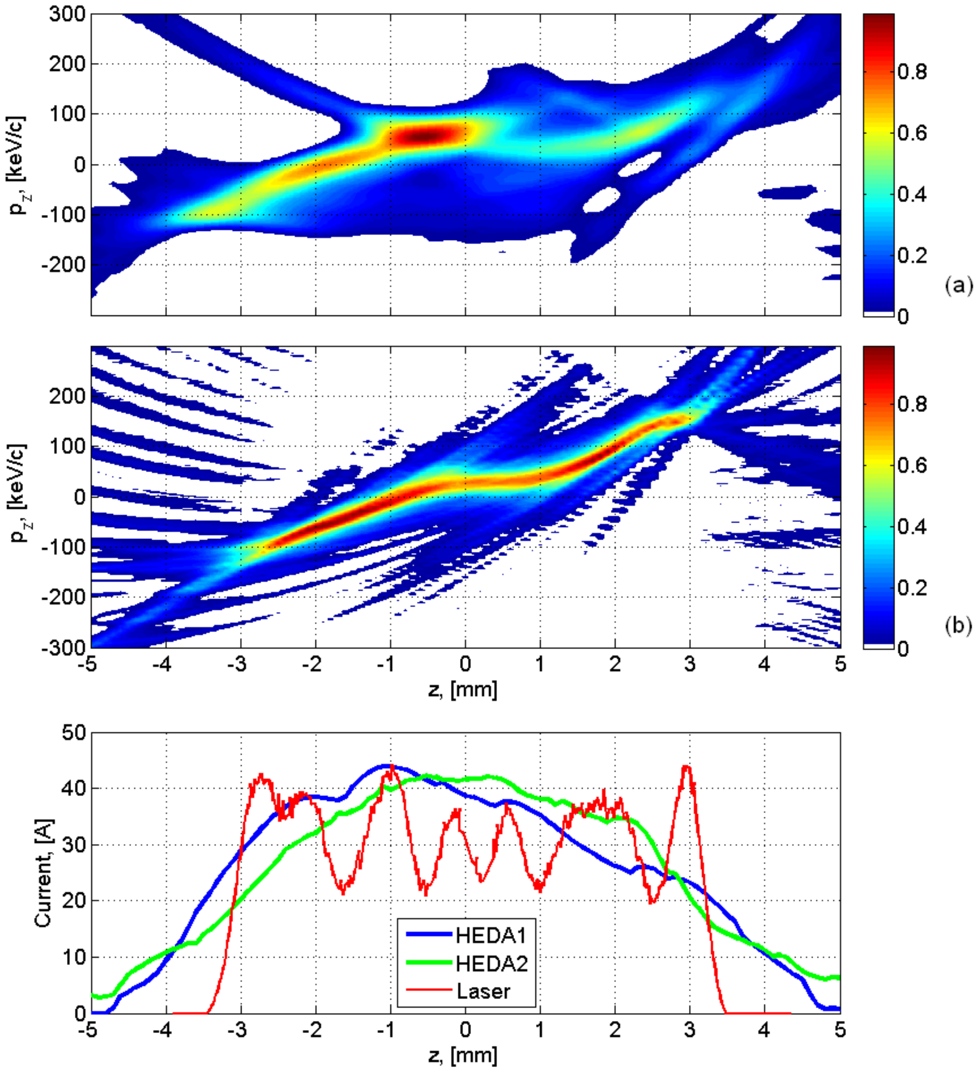
Laser Profile \ Bunch charge	20 pC	100 pC	700 pC	1 nC
Gauss, 2.7 ps	✓		✓	
Flat-top, 17.4 ps	✓	✓		✓
Modulated, 21.5 ps	✓			✓

Results for modulated laser pulse and 20 pC charge



Temporal structure of the laser profile can be recognized in the phase space density.

Results for modulated laser pulse and 1 nC charge



Space charge smears out the temporal structure of the laser during emission.

Momentum resolution gets worse.

Acceleration model does not fully work.

Measurements summary

- In all the reconstructed phase spaces **slice momentum spread** is much bigger than expected one from the numerical simulations:
  - **1.5 keV/c** momentum resolution is not sufficient,
  - **higher number of projections** should reduce the amount of **artifacts** in the reconstructed phase space.
- For the small charge of 20 pC and flat-top laser temporal profile the longitudinal structure of the reconstructed longitudinal phase space is in a **good agreement** with the laser temporal profile.
- For the higher charges the **space charge forces** start to play a significant role:
  - **momentum resolution** gets worse,
  - **acceleration model** does not fully describe longitudinal phase space transformation during acceleration and beam transport.

- 1. Motivation
- 2. RF deflector
- 3. Longitudinal phase space tomography
- 4. PITZ facility overview
- 5. Experimental results using tomographic technique
- **6. Conclusions and outlook**

Conclusions

- Two techniques for longitudinal phase space measurements at the PITZ beamline were presented and described (TDS and tomography).
- Simulations of measurements for both techniques were performed and studied as a proof of principle.
- First longitudinal phase space measurements using tomographic technique were performed at PITZ for different bunch charges and various laser temporal profiles.
- For the low charge the temporal structure of the reconstructed phase space is in good agreement with the laser profile.
- To have better agreement with the numerical simulations much higher momentum resolution is required (< 1 keV/c) and more momentum projections are needed.
- Tomographic technique can be used for longitudinal phase space characterization while other techniques are not available yet.

Outlook

- TDS installed at PITZ is the prototype of the TDS for the European XFEL to test its efficiency and performance. First tests are planed for the end of this year.
- TDS will allow measurements of the slice beam properties. Together with HEDA2 it will give the possibility for direct longitudinal phase space measurements.
- Self-modulation experiments are planned at PITZ. TDS is a necessary tool to perform studies of the bunch energy modulation caused by interaction with plasma.
- Comparison of the experimental results from TDS and tomographic technique need be performed.
- Simulation of tomographic measurements using the real laser temporal profile are still needed.

Acknowledgements

My sincerest gratitude is addressed to:

G. Asova, M. Groß, I. Isaev, M. Khojoyan, G. Kourkafas, M. Krasilnikov, M. Otevrel, J. Rossbach, T. Rublack, F. Stephan, G. Vashchenko.

Thank you for your attention!

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