# Two techniques for longitudinal phase space measurements at PITZ

1. Motivation
2. RF deflector
3. Longitudinal phase space tomography
4. PITZ facility
5. Experimental results
6. Conclusions and outlook


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Humboldt-Universität zu Berlin
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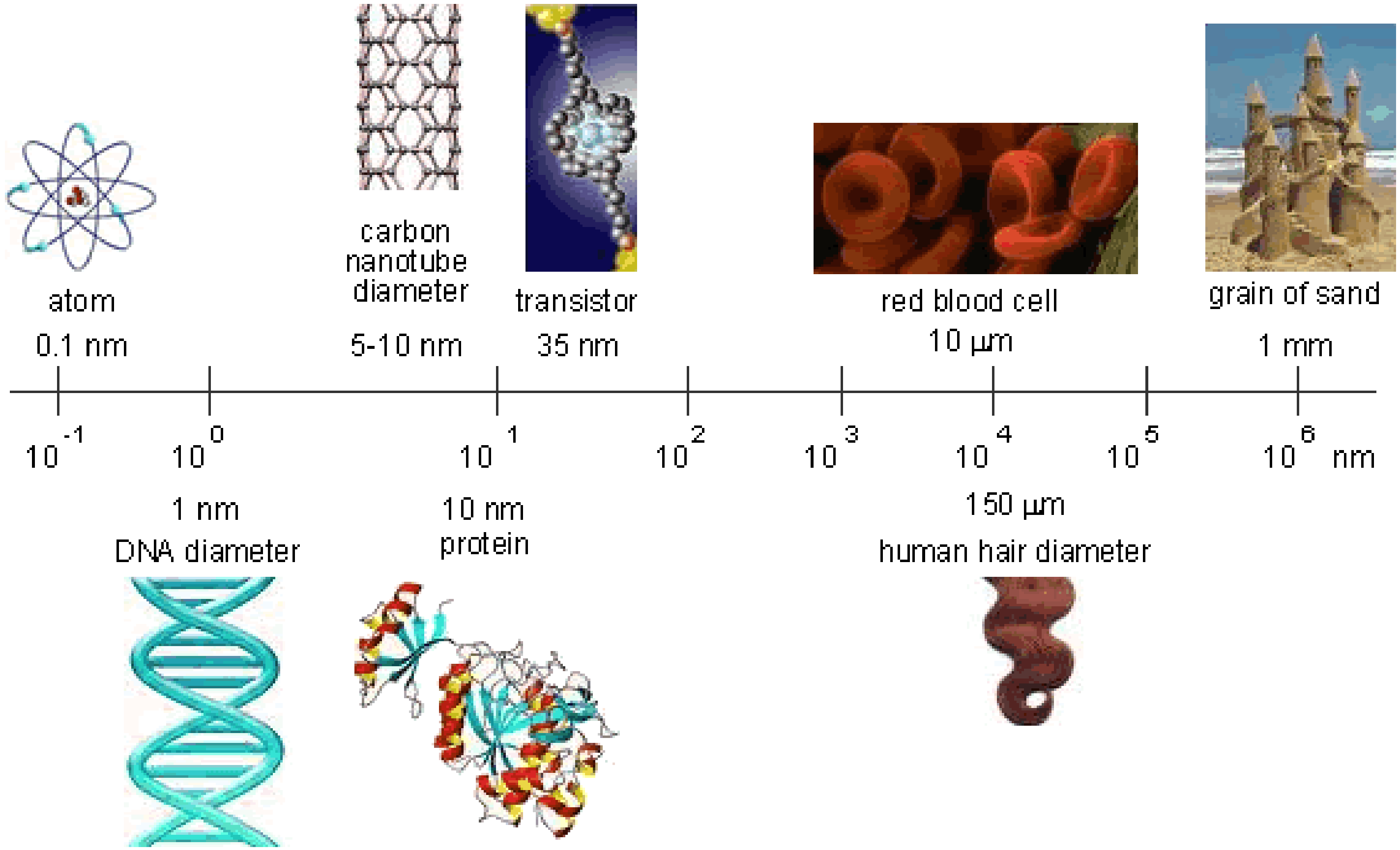
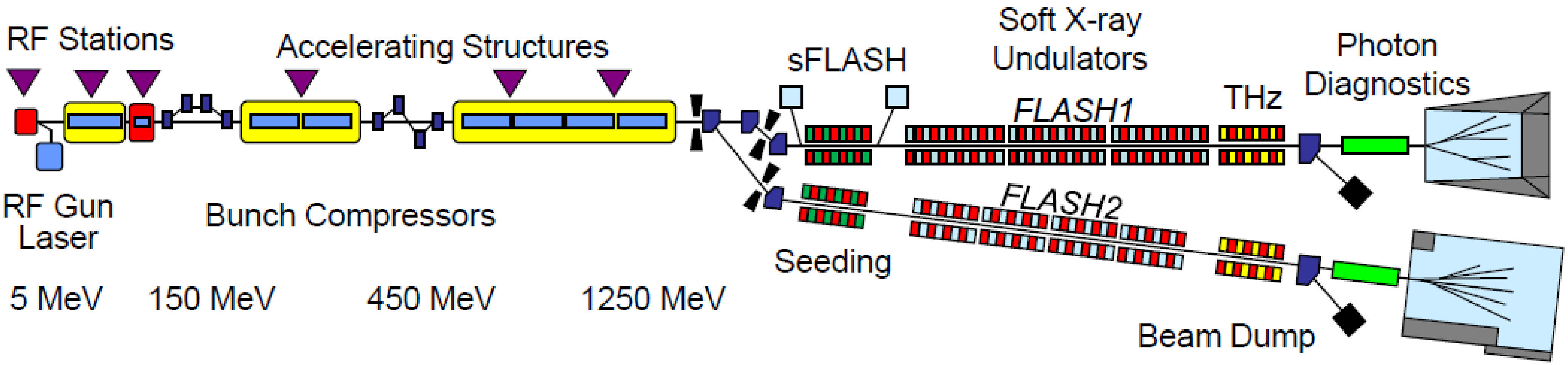
HELMHOLTZ GEMEINSCHAFT

DESY

# Length scales



# FEL in Hamburg - FLASH



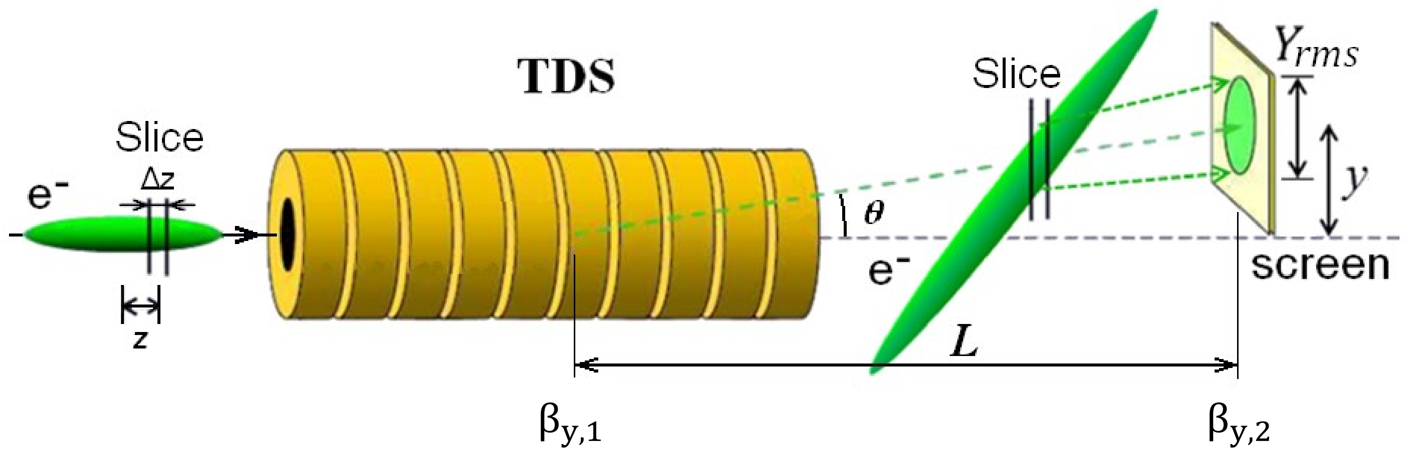
# Electron bunch characterization

| Characteristic: | Dimension: | Origin: | Diagnostic: |
|---|---|---|---|
| Bunch charge | C, nC | Electron source | FC, ICT, … |
| Bunch energy | eV, MeV, GeV, TeV | Acceleration (RF fields) | Magnet spectrometer, … |
| Bunch transverse size | m, mm, µm | Emittance, transverse phase space (electron source, beam optics) | Screen, wire scanner, … |
| Bunch length | m, mm, µm s, ps, fs | Energy spread, longitudinal phase space (electron source, acceleration, compression) | Streak camera, RF deflector, tomography technique, … |



DESY

# RF deflector




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

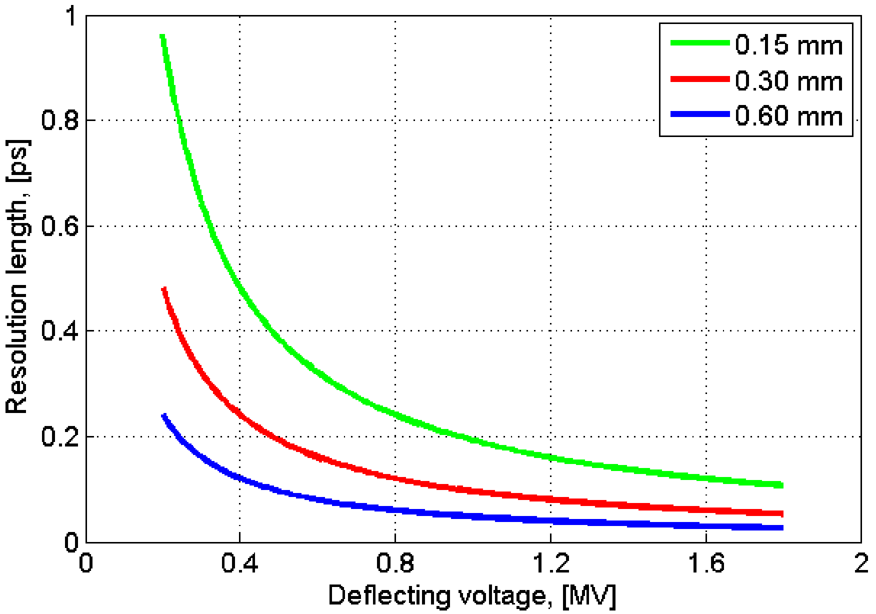
$$S = \frac{eV_0 k}{pc} L,$$

$$z_1 \geq \frac{\sqrt{\beta_{y,2} \cdot \varepsilon_y}}{S},$$

$$S = \sqrt{\beta_{y,2} \cdot \beta_{y,1}} \cdot \sin\left(\Delta\psi_y\right) \cdot \frac{eV_0 k}{pc},$$

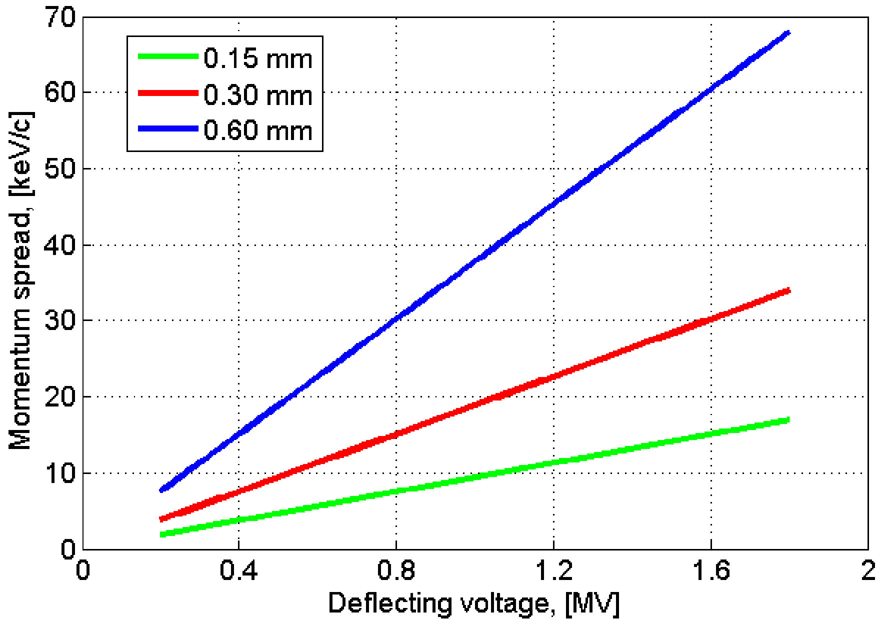
# Resolution length

$$z_1 \geq \frac{\sqrt{\varepsilon_y}}{\sqrt{\beta_{y,1}} \cdot \sin(\Delta\psi_y)} \cdot \frac{pc}{eV_0 k}.$$

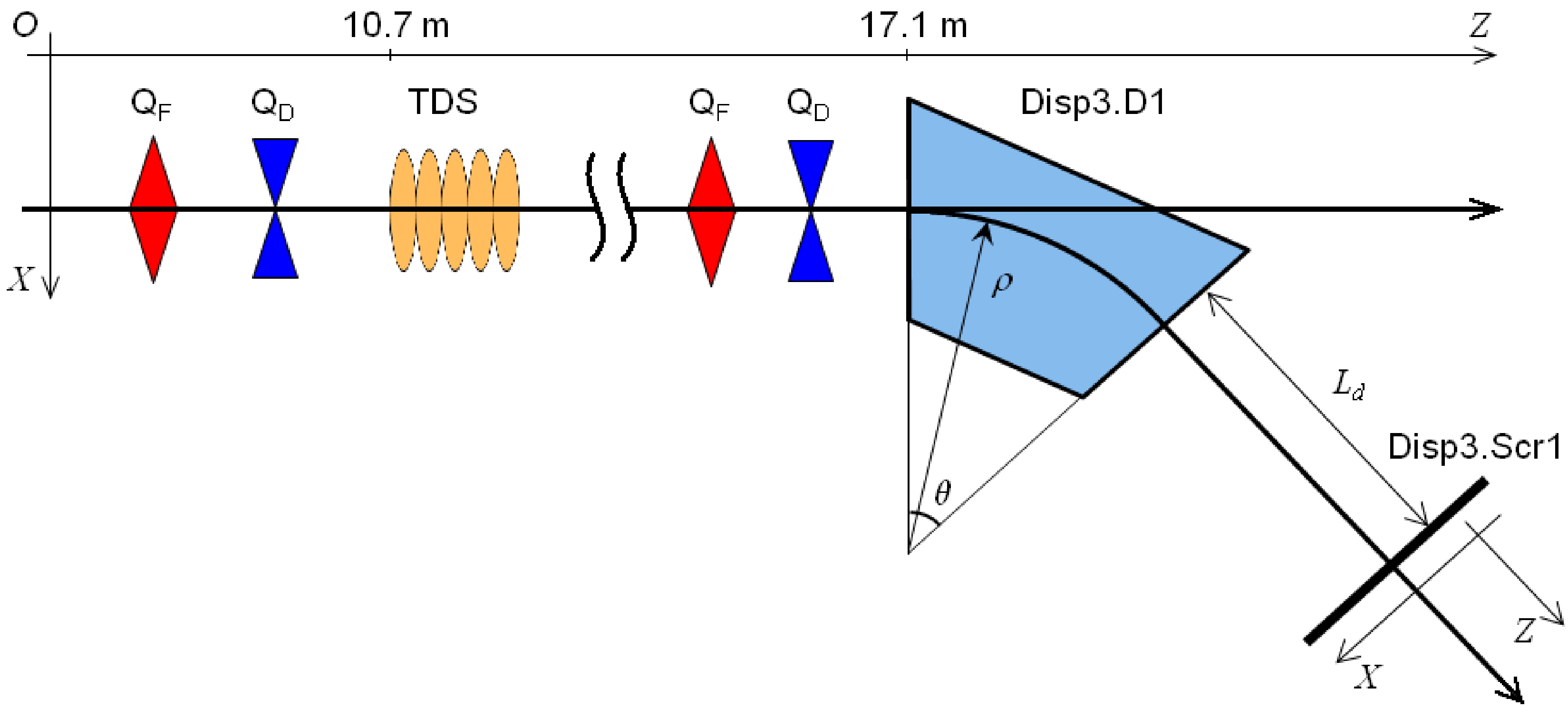


# Induced momentum spread

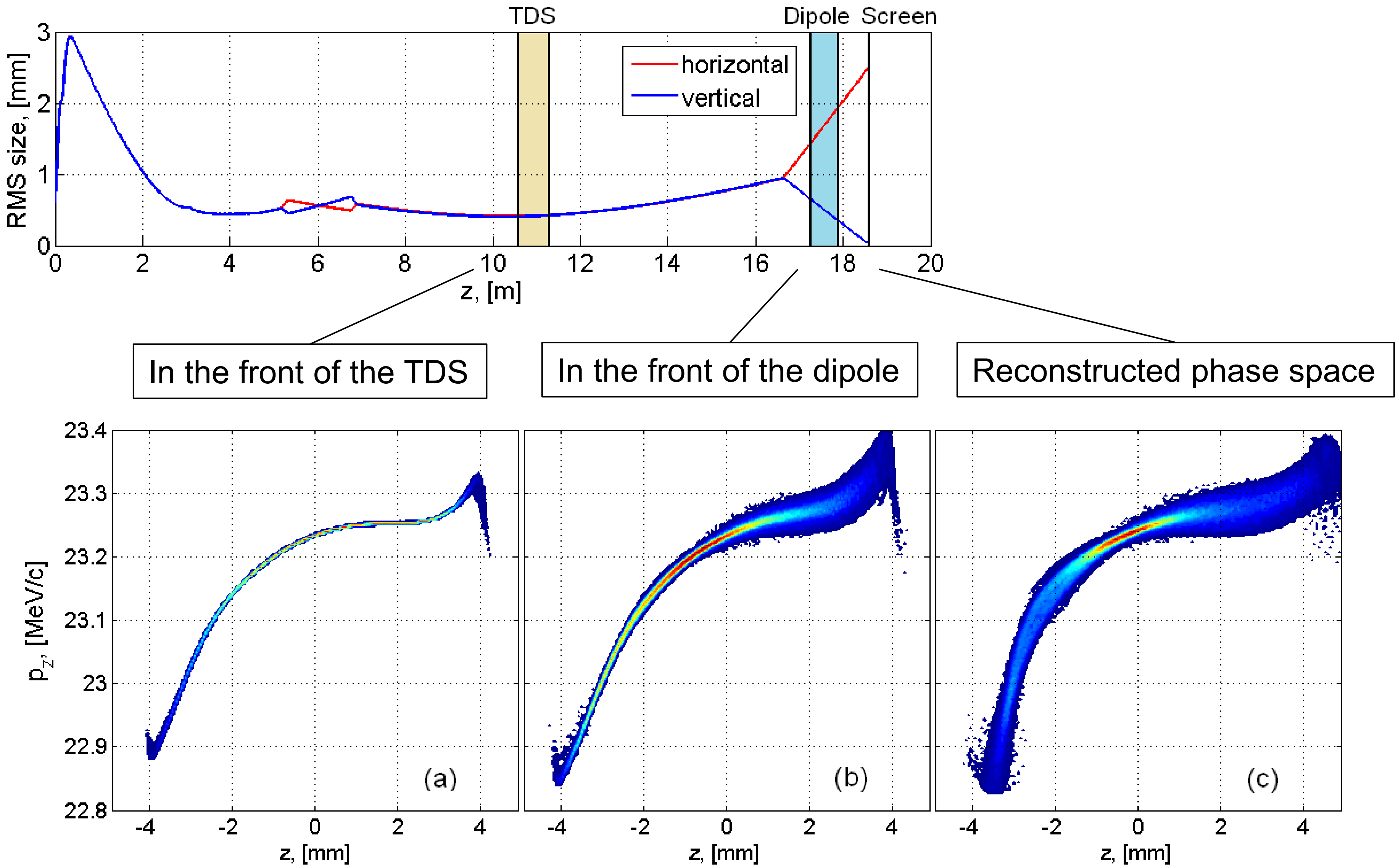
$$\sigma_\delta = \frac{eV_0 k}{p_0 c} \cdot \sigma_y.$$



# Longitudinal phase space measurements with TDS



# Numerical simulation of measurements



# RF deflector, summary

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

+ Direct, single shot measurements

− Expansive and complicated in realization

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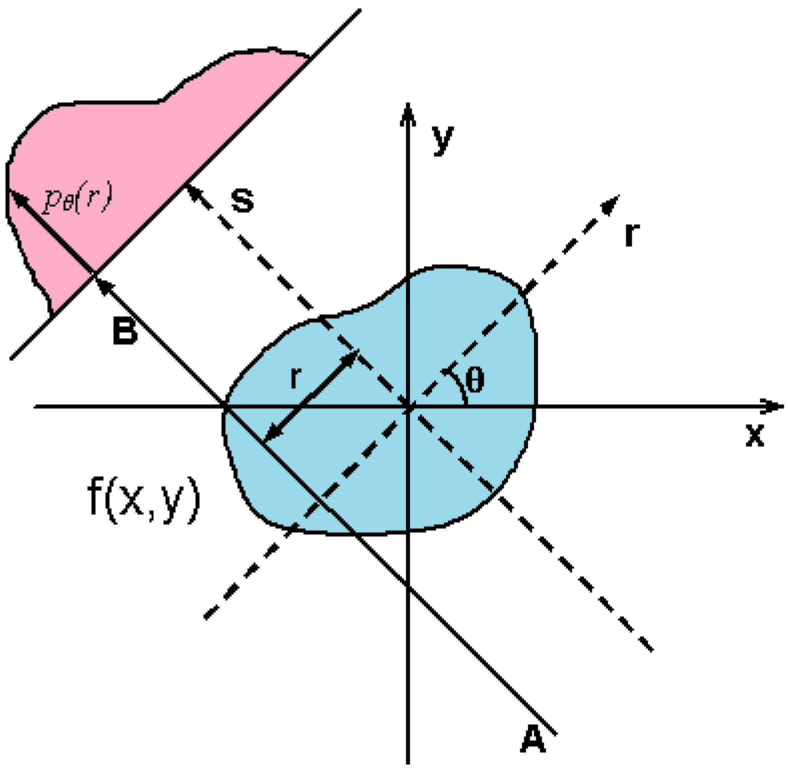
# Tomography



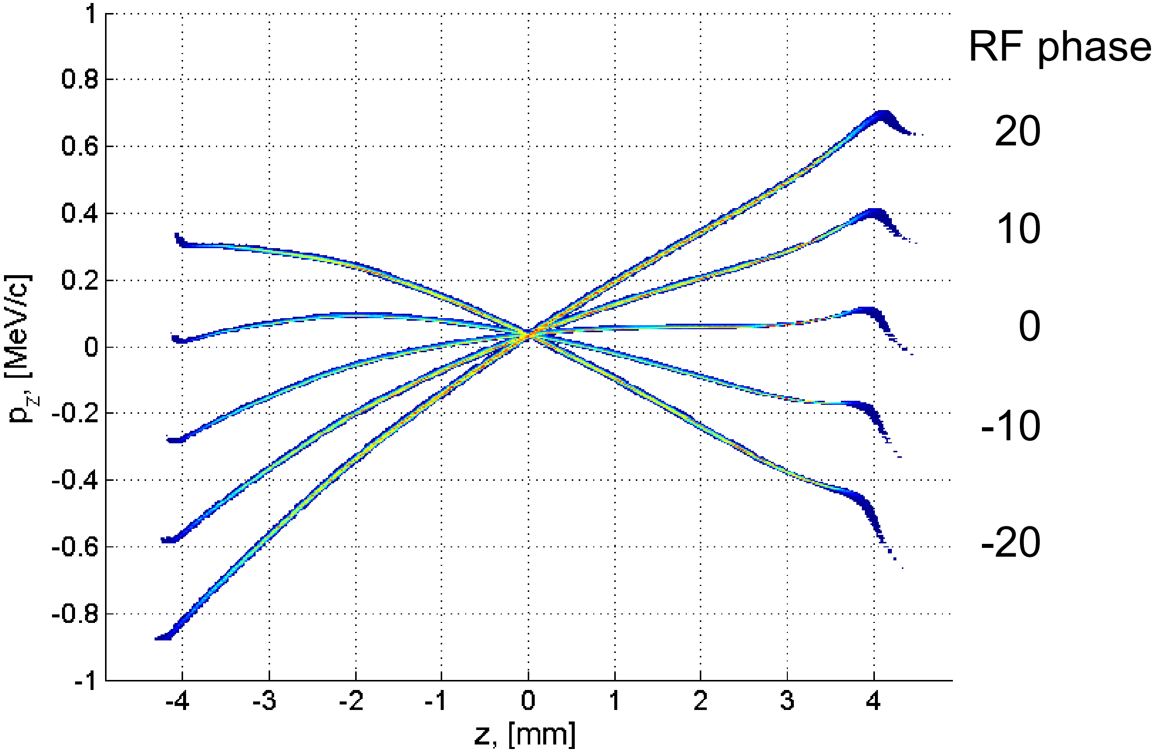

There is unknown object $f(x, y)$ and one can measure projection of this object $p_\theta(r)$ at different angle $\theta$.

Resulted projections $p_\theta(r)$ are called tomography transformation of the object $f(x, y)$.

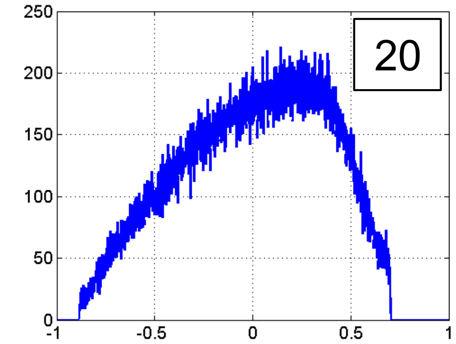
Procedure to restore unknown object from the set of projections is called inverse tomography transformation.

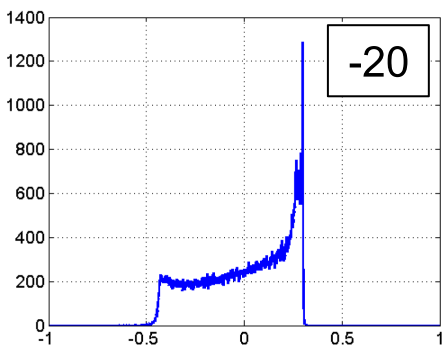
This procedures can be applied to the longitudinal phase space.

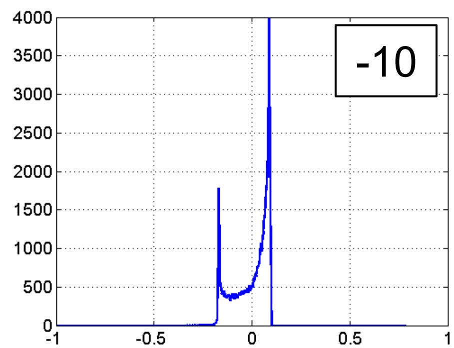
# Simulated longitudinal phase spaces, 1 nC charge

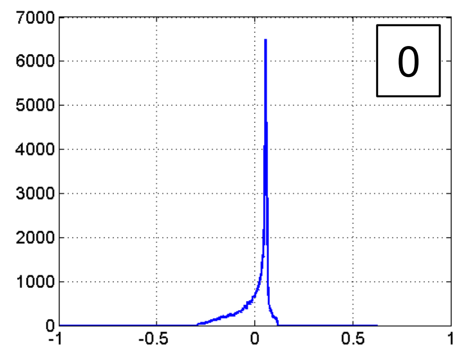


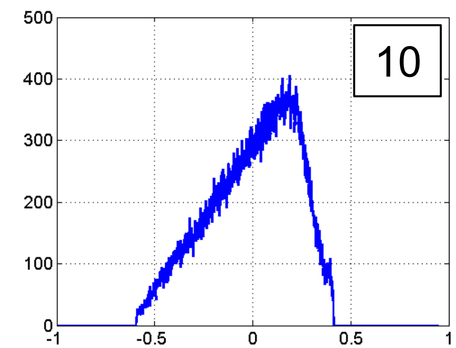

Simulated electron bunch longitudinal phase spaces for different booster RF phases.



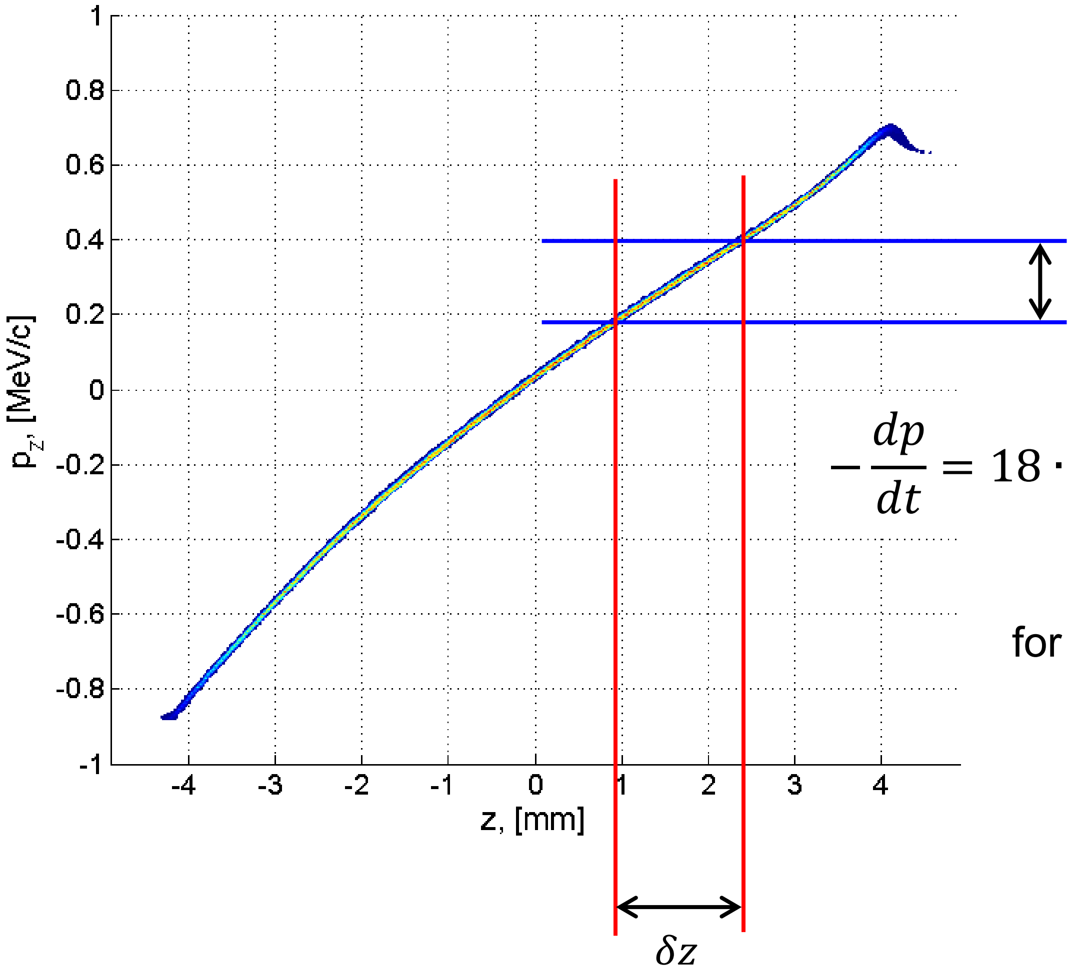



# Longitudinal resolution




$$p = 6.7Mev/c + 18Mev/c \cdot cos(\varphi)$$

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

for 20° phase offset $k = \frac{dp}{dt} = 50 \frac{keV/c}{ps}$

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

for $\delta p = 5\ keV/c$ → $\delta z = 0.1\ ps = 30\ \mu m$

# Algebraic reconstruction technique (ART)

$$g_q^{(k+1)} = g_q^{(k)} + \sum_{ij} \frac{a_{ijq}[p_{ij} - \sum_l a_{ijl} \cdot g_l^{(k)}]}{\sum_{nm} a^2{}_{inm}}$$

$g_l^{(k+1)}$– phase space image after $k + 1$ iterations

$g_l^{(0)}$– zero phase space or initial guess

$i$ – phase (Nphase)

$j$ – momentum (Npz)

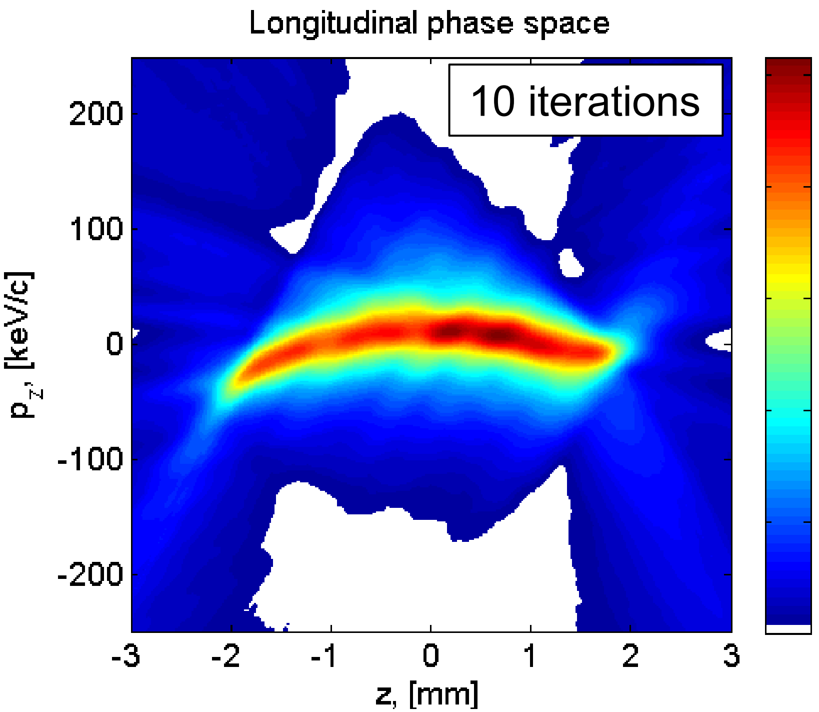
$q, l$ – image index (Nl = Npz*Nz)

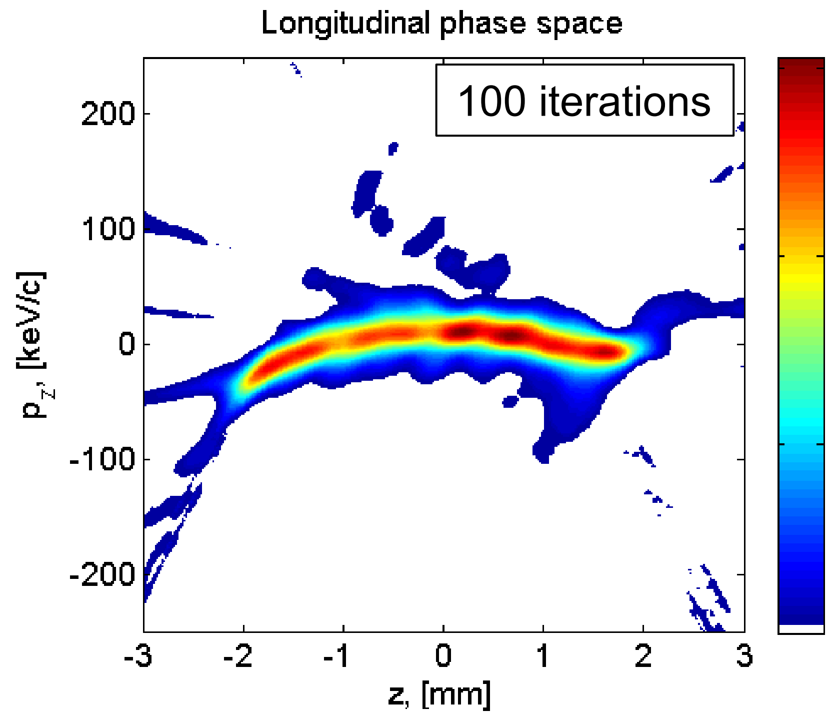
$k$ – iteration number

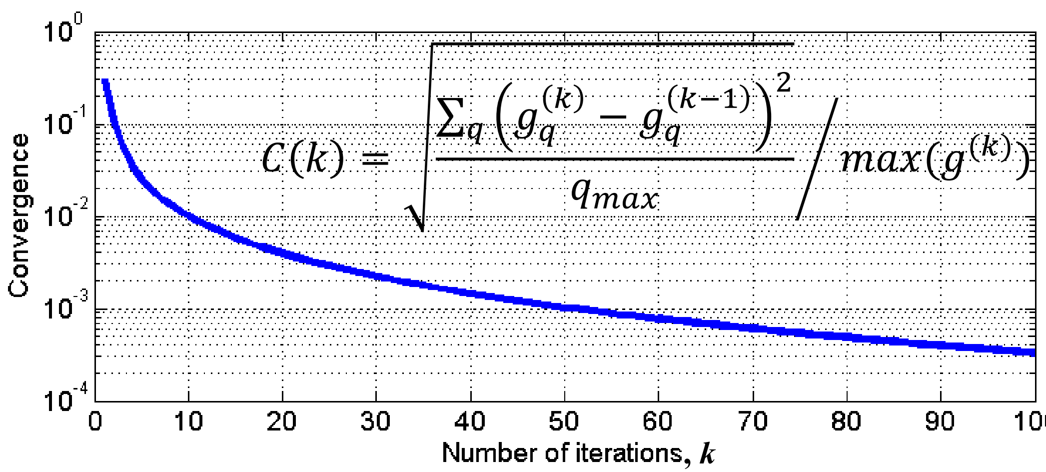
$$p_{ij} = a_{ijl} \cdot g_l$$

$$p(z, \varphi) = 6.7Mev/c + 18Mev/c \cdot cos(\varphi)$$

# Example of ART reconstruction



# Tomography, summary

+ Diagnostic technique for longitudinal phase space measurements:

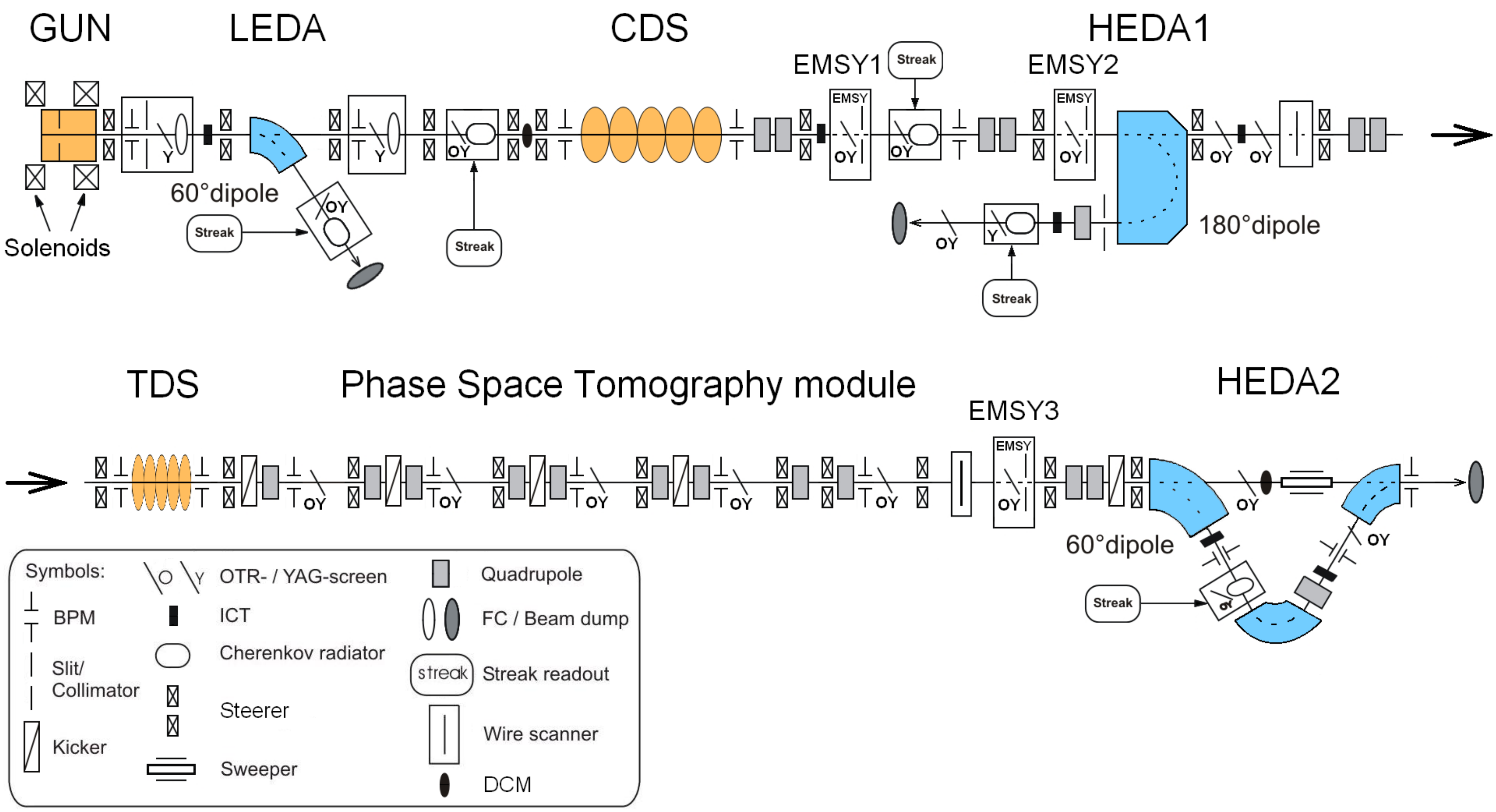
  bunch temporal profile (current distribution)

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

− Multi shot measurements

− Sophisticated data treatment

# The Photo Injector Test facility, Zeuthen site (PITZ)

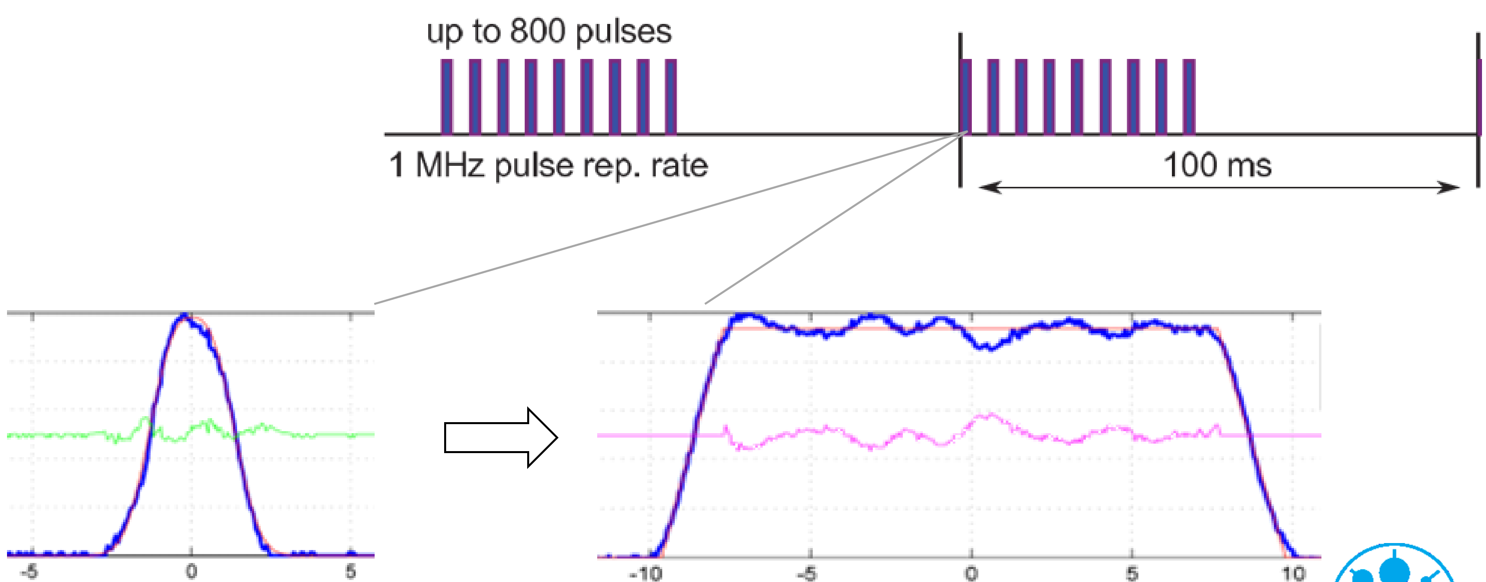


# The Photo Injector Test facility, Zeuthen site (PITZ)

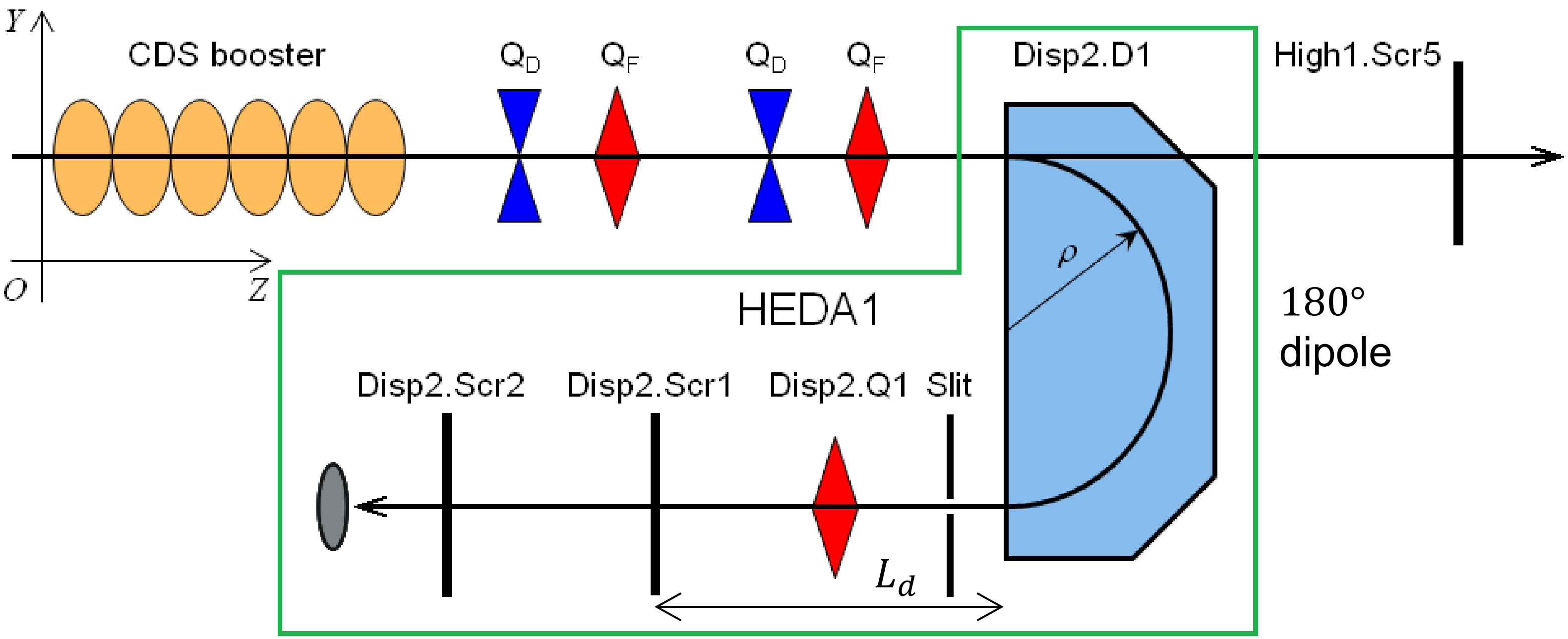
PITZ photo injector main parameters:

| | |
|---|---|
| Bunch charge | 0 … 4 nC |
| Repetition rate | 10 Hz |
| Beam momentum after gun | 0 … 7 MeV/c |
| Beam momentum after booster | 0 … 27 MeV/c |
| Number of bunches | 1 … 800 |
| Bunch spacing | 1 us |
| Laser pulse temporal shape | 2 ps Gauss … 22 ps flat-top |

Laser pulse train structure:



# HEDA1 momentum measurements

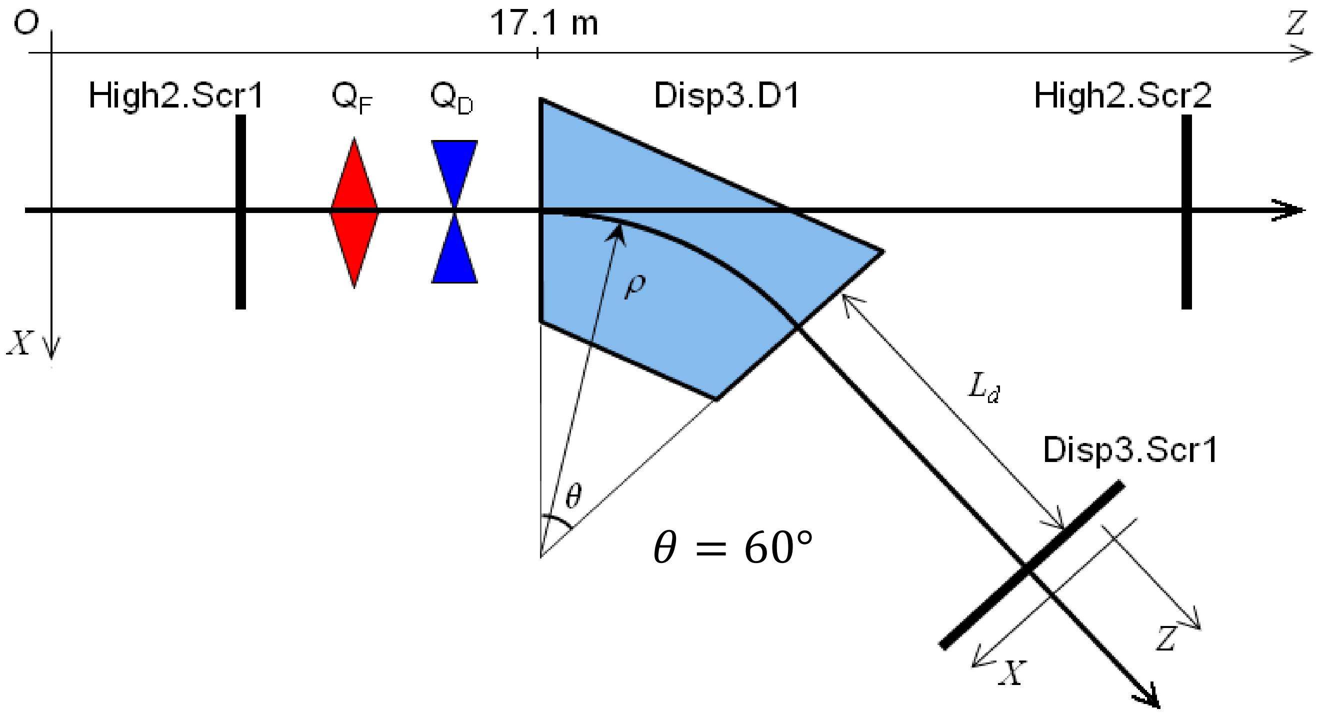



Dispersion $D_y = \rho(1 - cos(\theta)) + L_d sin(\theta) = 2\rho$ = 0.6 m

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

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

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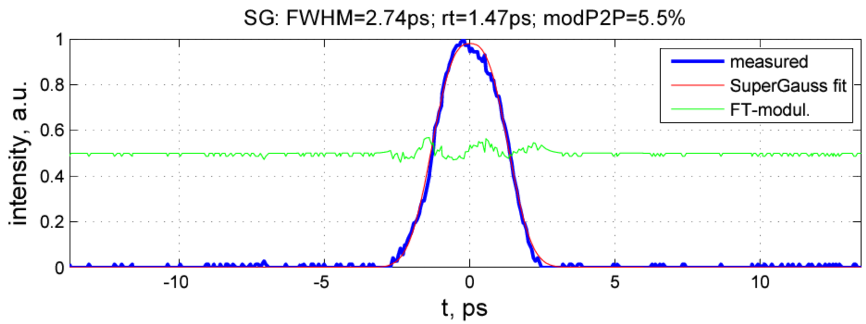
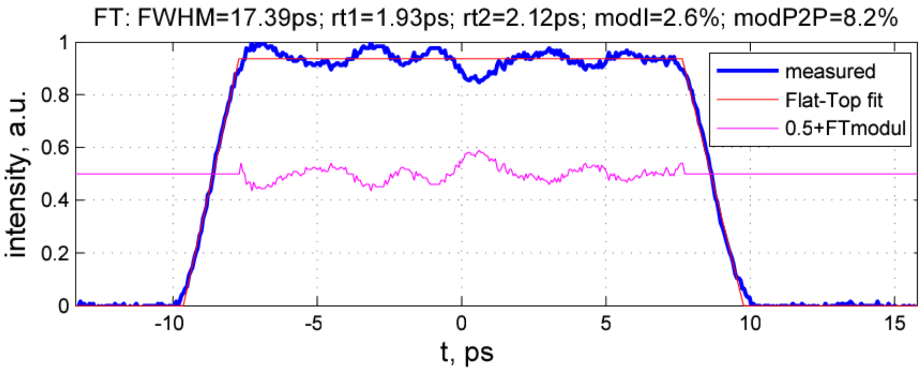
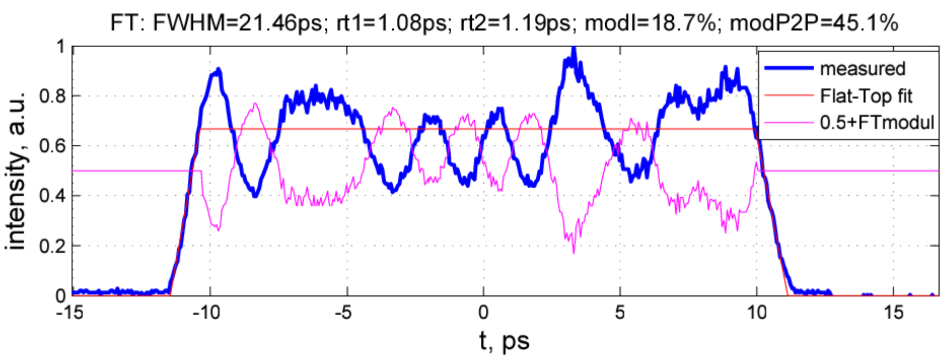
# Used laser profiles for the measurements



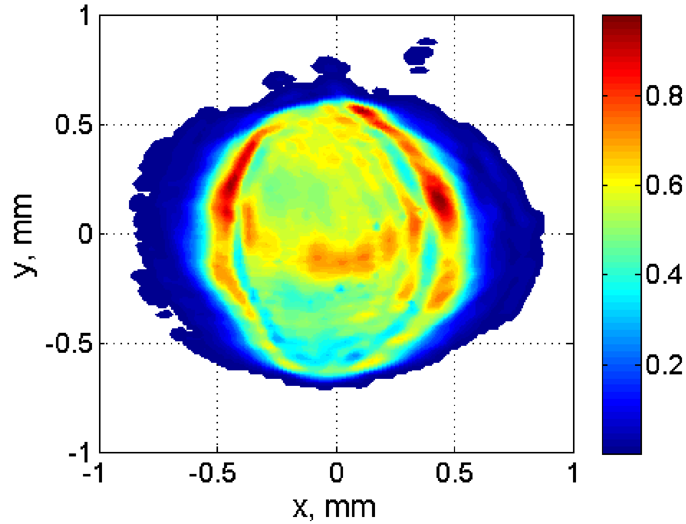

2.74 ps




17.4 ps

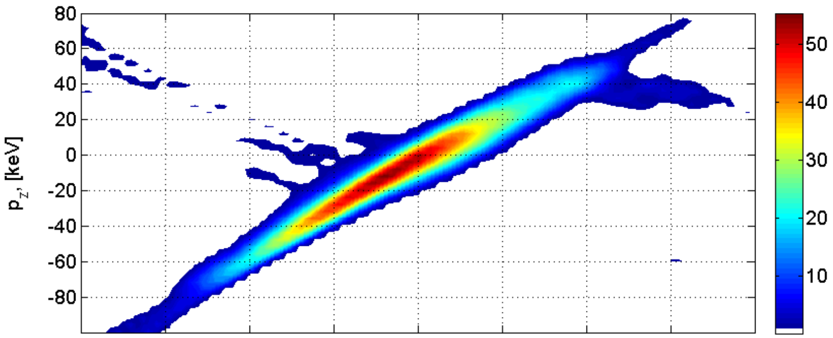
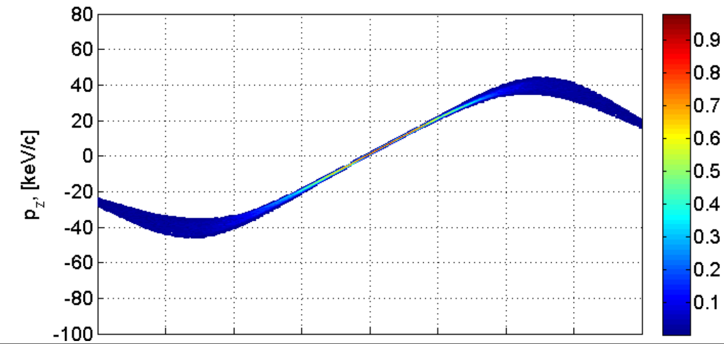
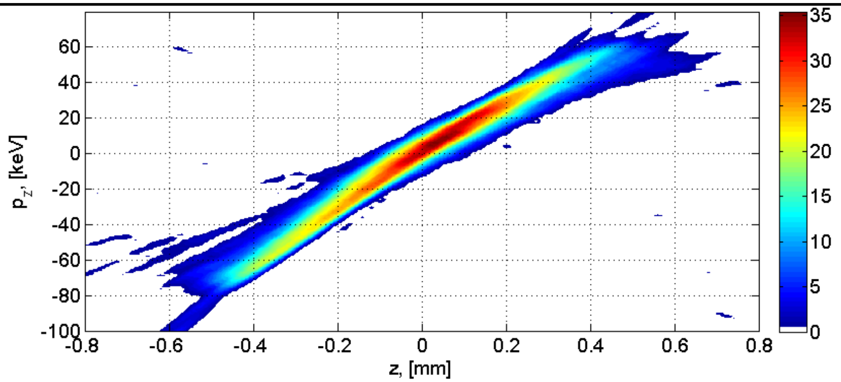
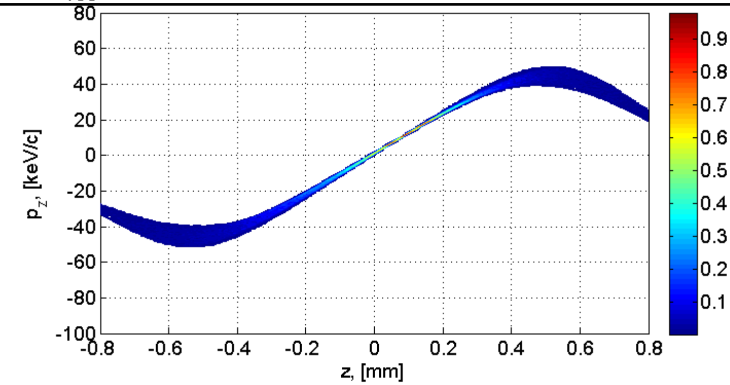



21.5 ps




x RMS = 0.36 mm
y RMS = 0.37 mm

# Gauss, 20 pC

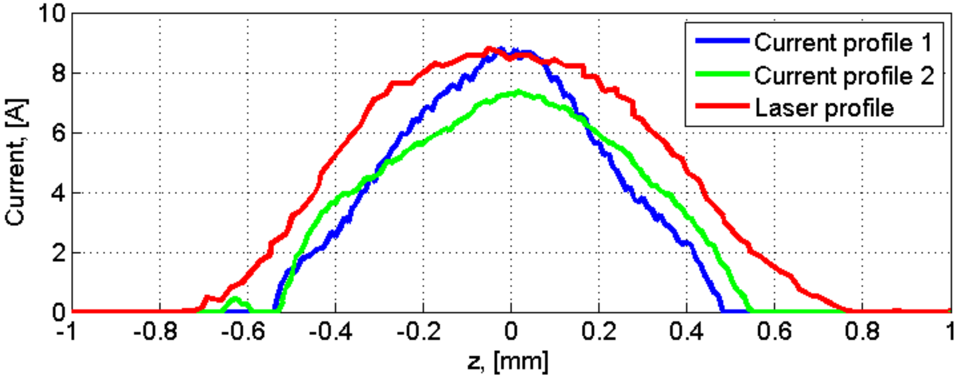
| | Measured | Simulated |
|---|---|---|
| HEDA1 |  |  |
| HEDA2 |  |  |

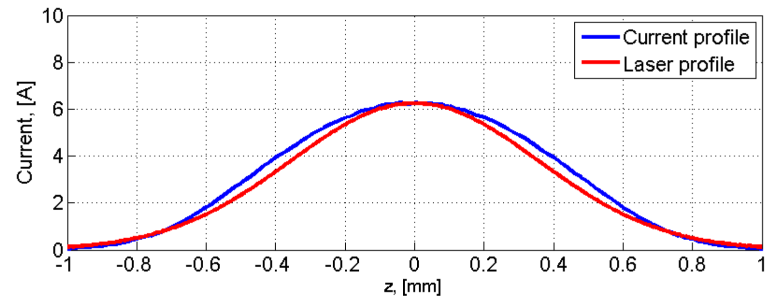




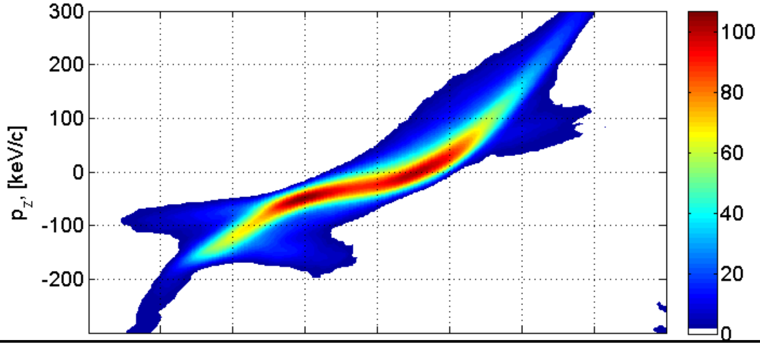
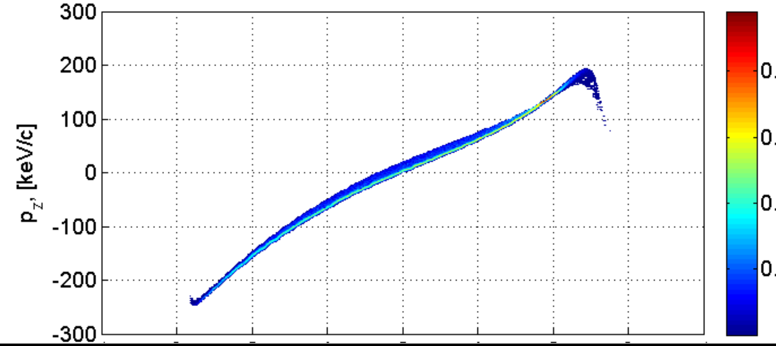
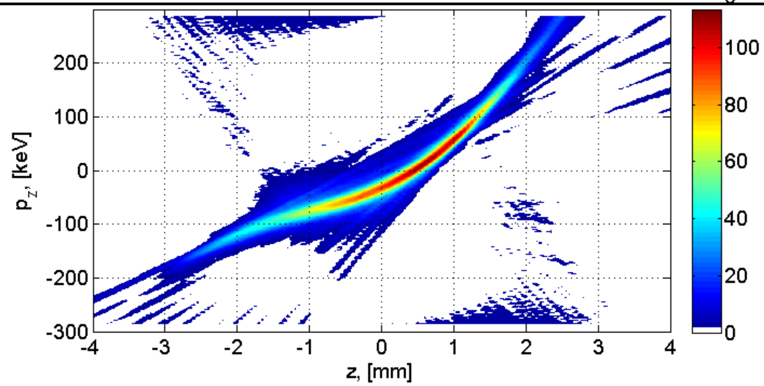
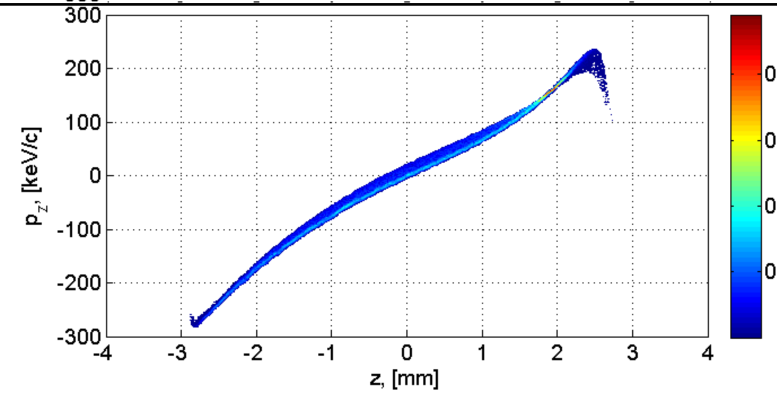




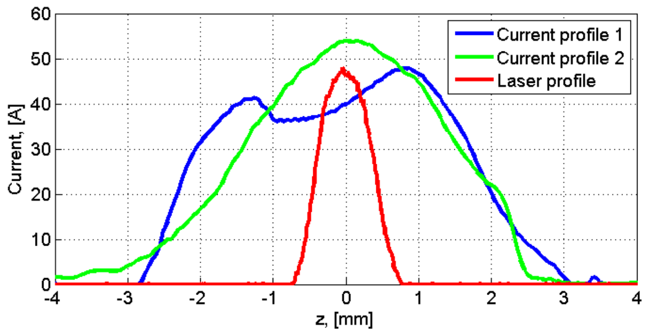


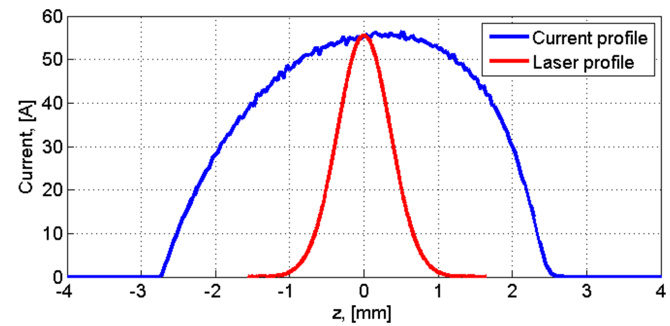
# Gauss, 700 pC

| | Measured | Simulated |
|---|---|---|
| HEDA1 |  |  |
| HEDA2 |  |  |

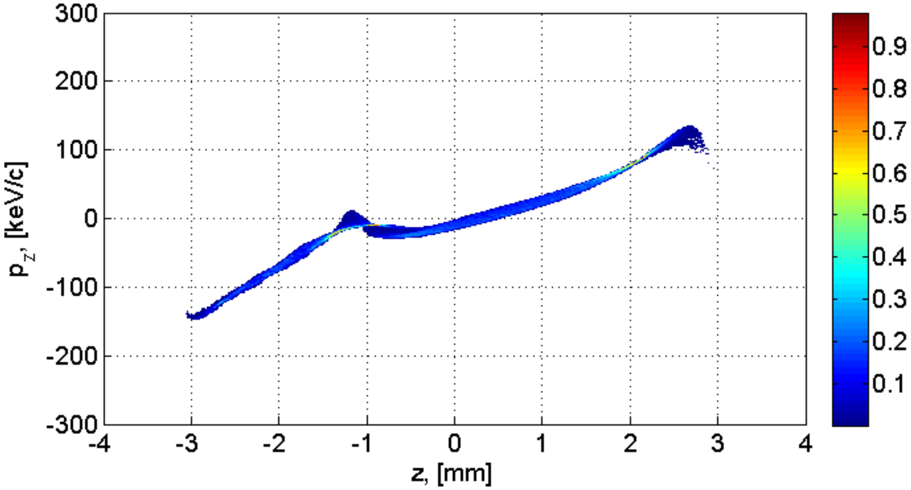


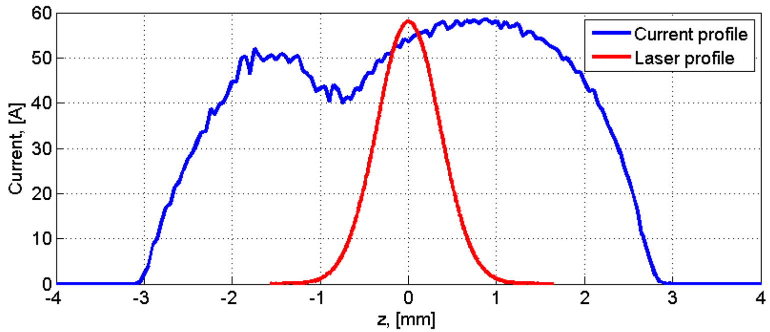






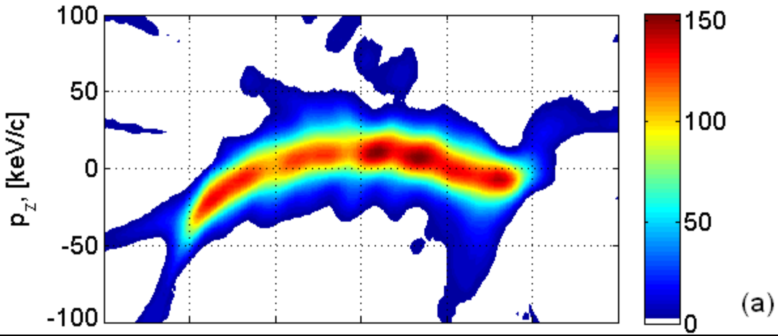
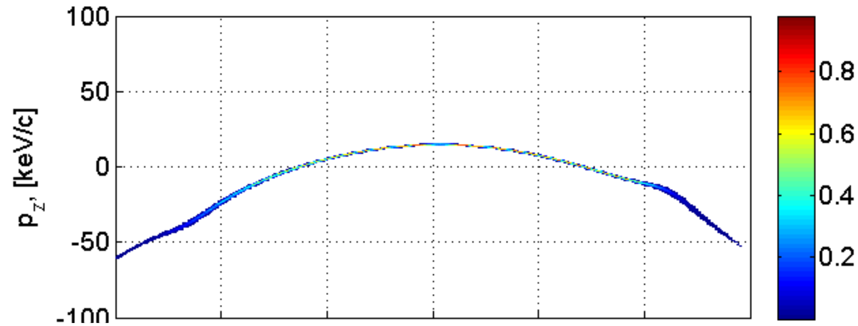
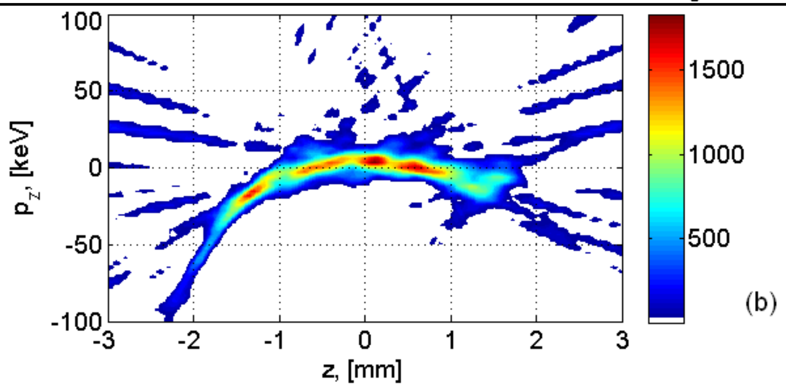
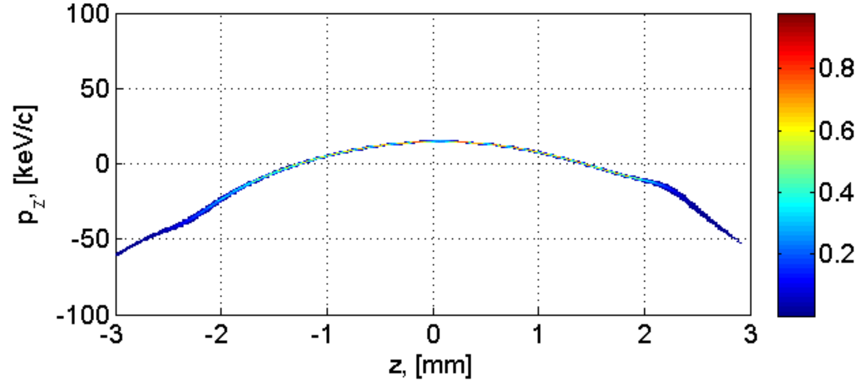
# Gauss, simulation

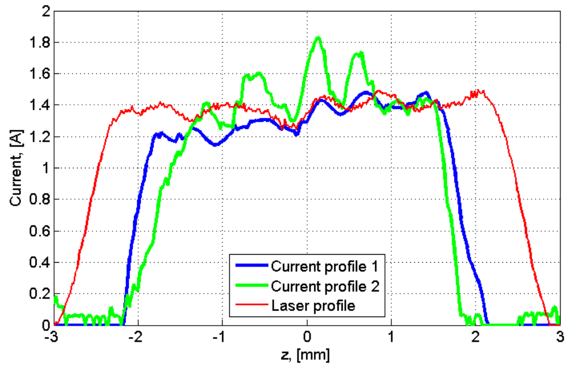


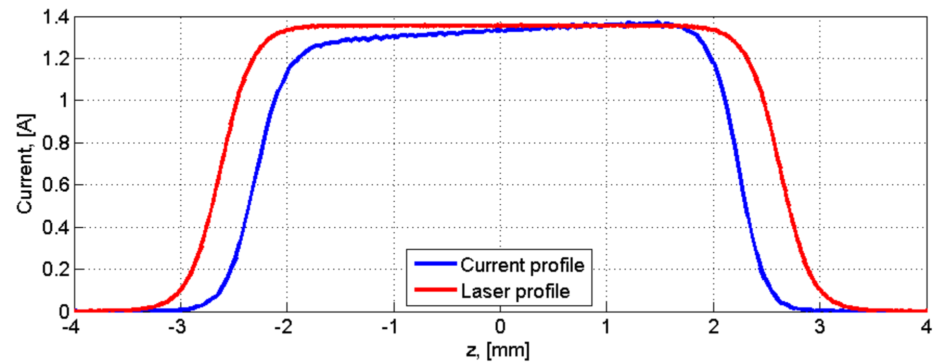




For this simulation the laser was set to 2 nC, but extracted charge was only 0.84 nC.

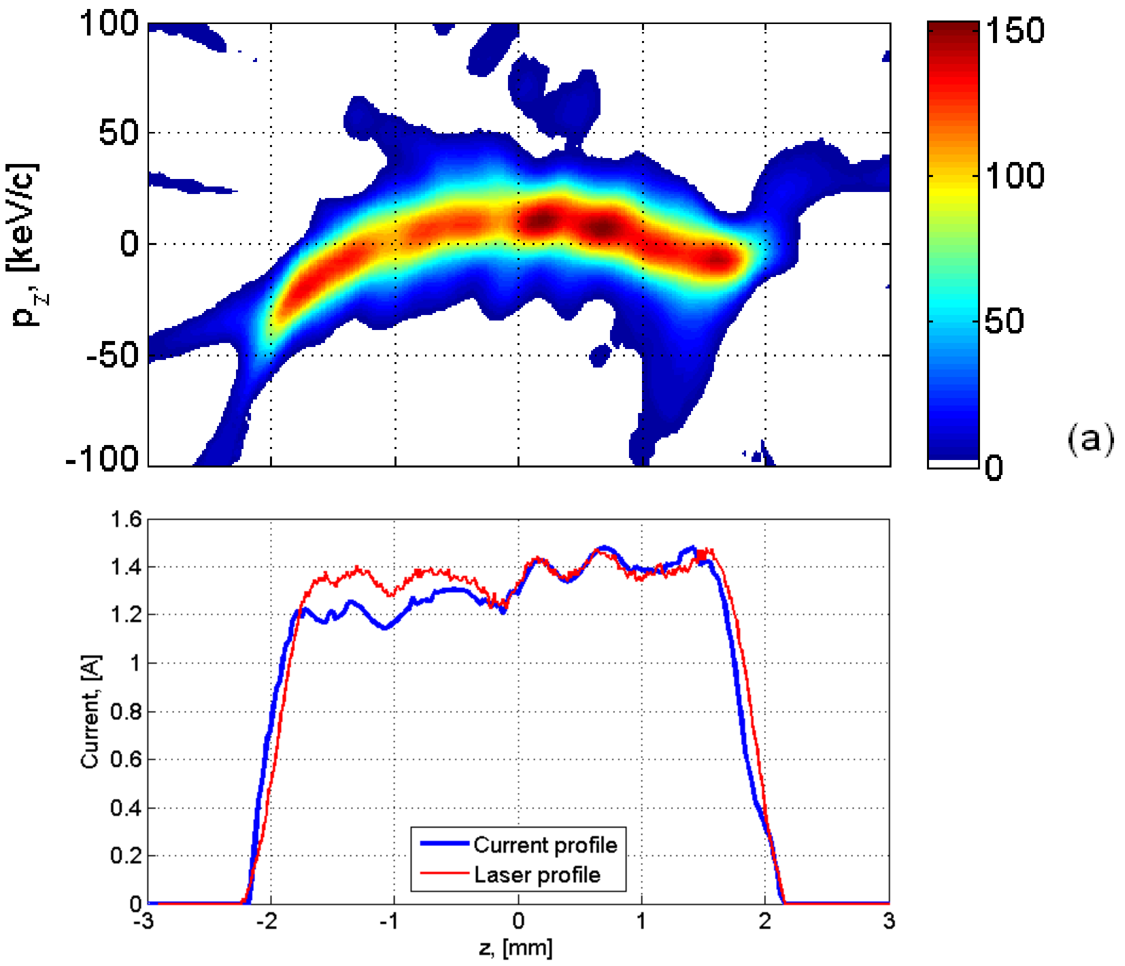
# Flat-top, 20 pC

| | Measured | Simulated |
|---|---|---|
| HEDA1 |  |  |
| HEDA2 |  |  |

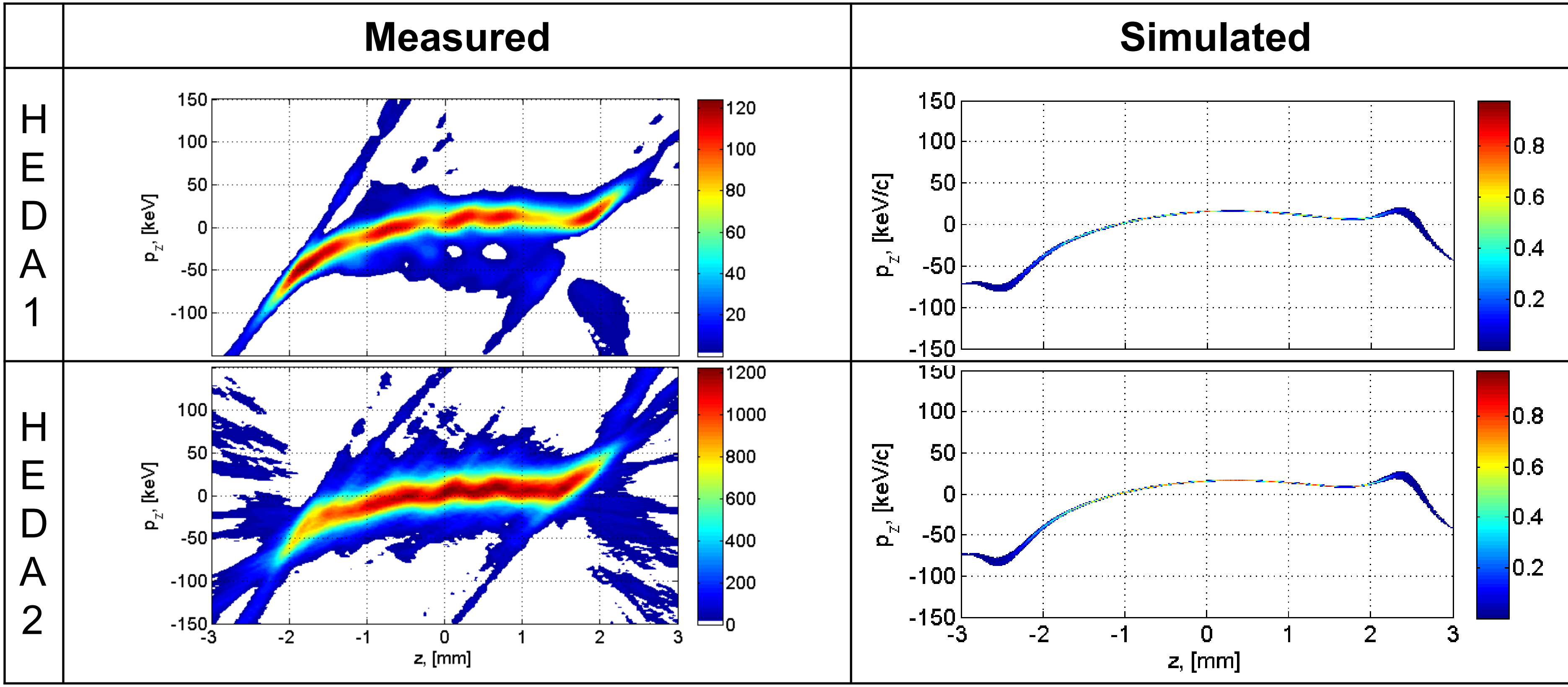


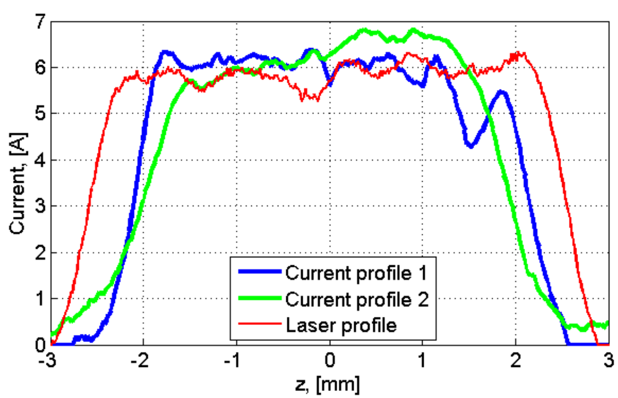



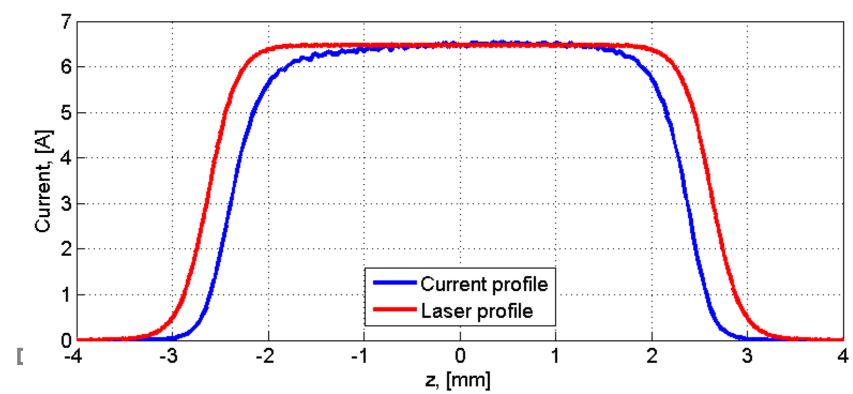
# Flat-top, 20 pC



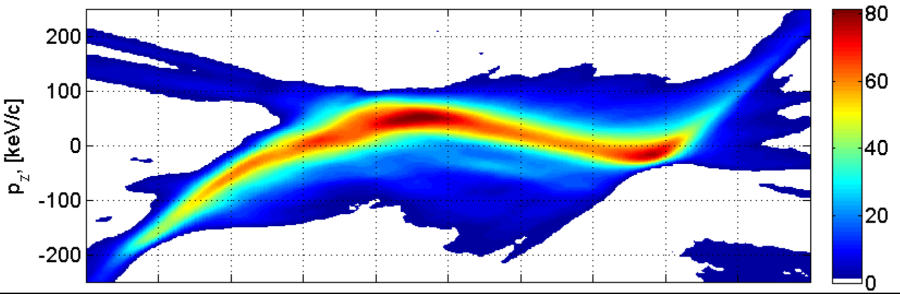
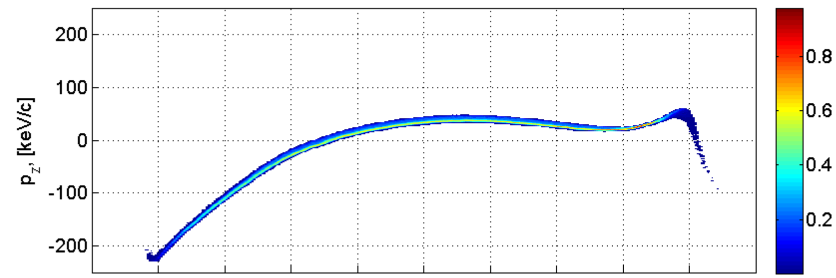
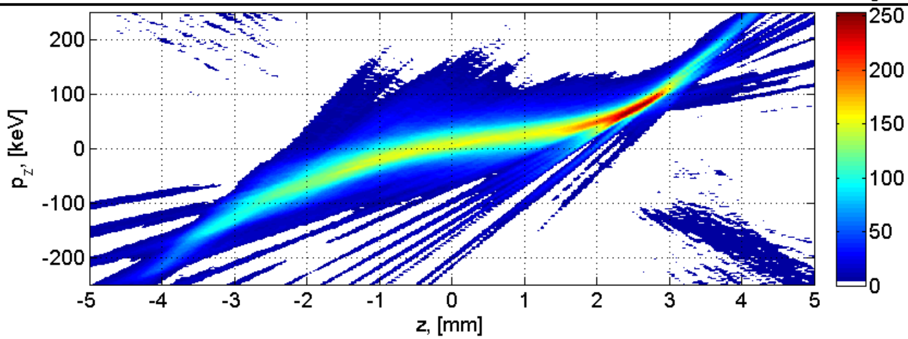
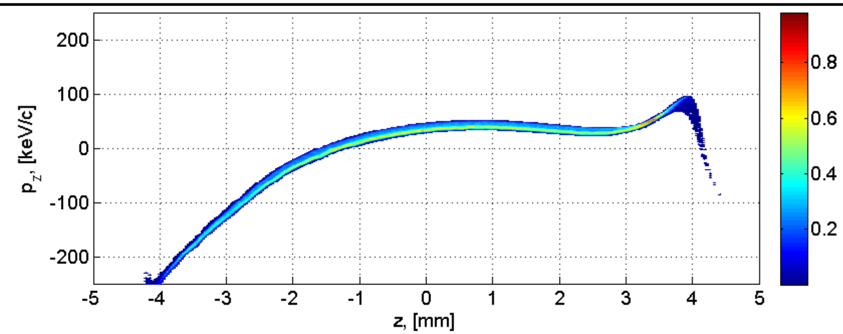
# Flat-top, 100 pC

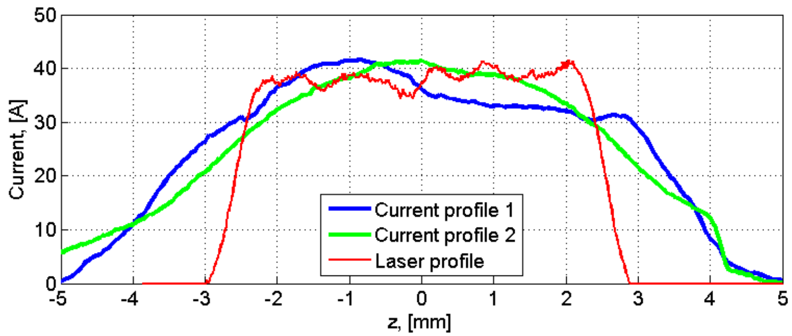


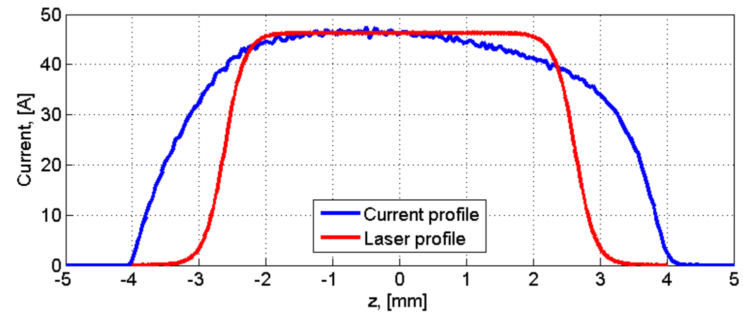



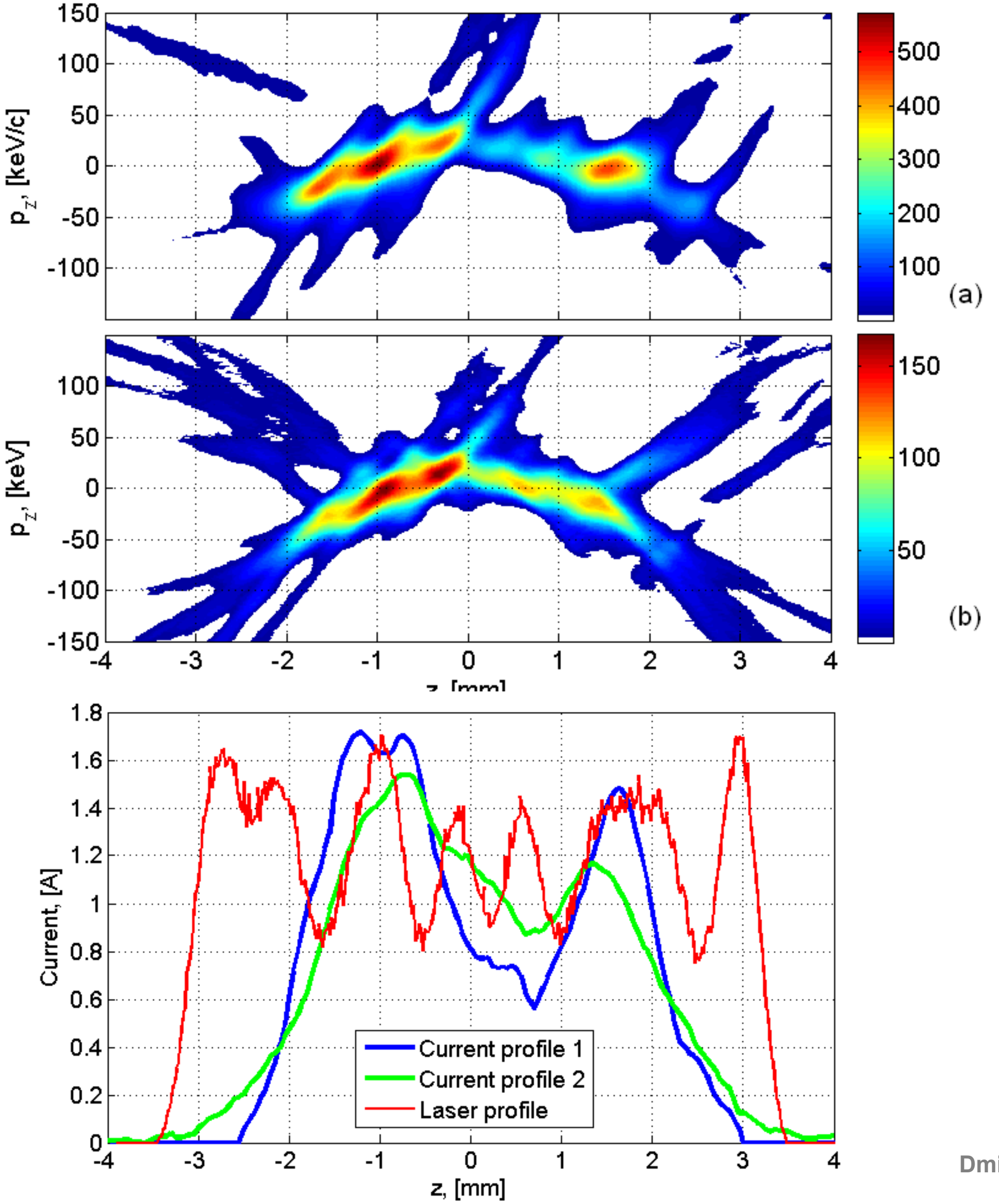
# Flat-top, 1 nC

| | Measured | Simulated |
|---|---|---|
| HEDA 1 |  |  |
| HEDA 2 |  |  |

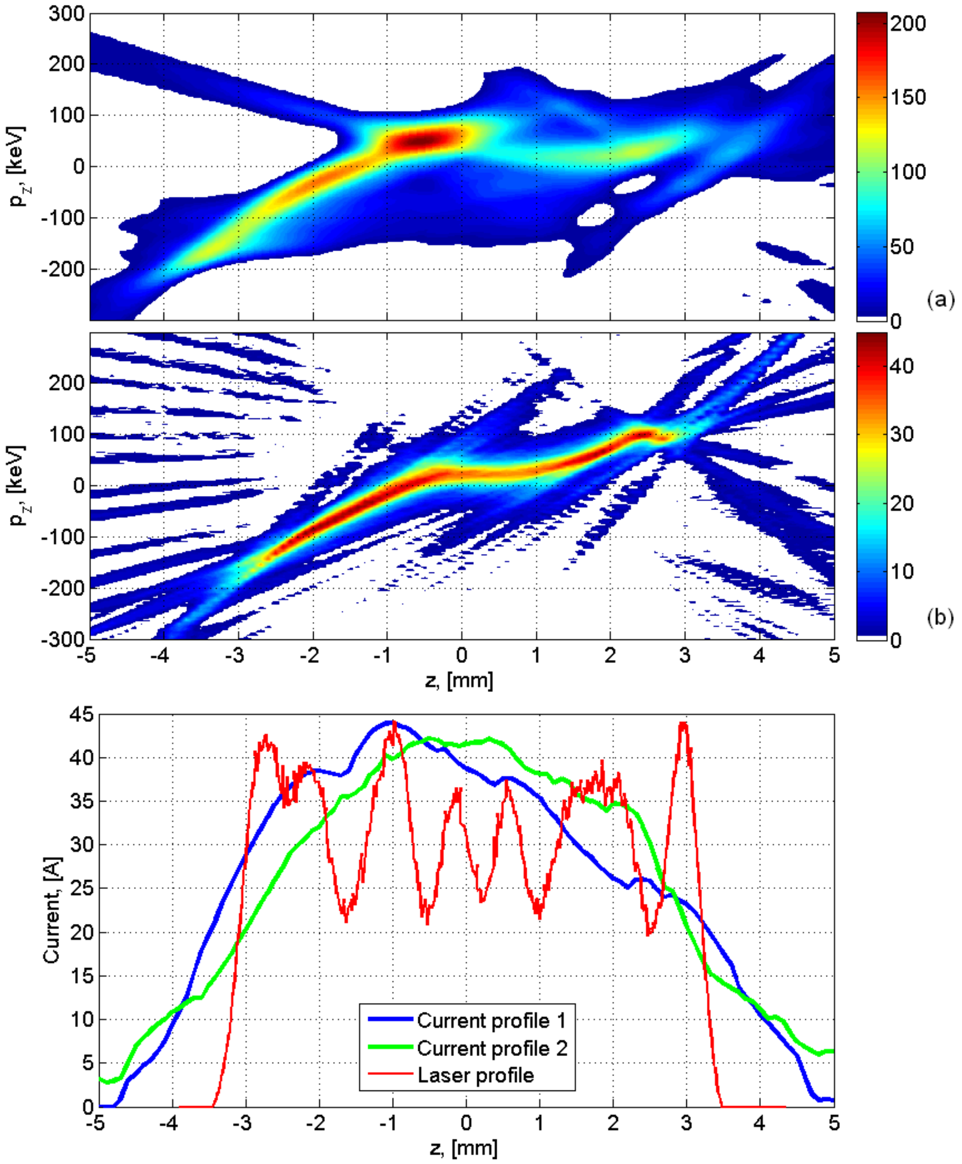


# Modulated flat-top, 20 pC



# Modulated flat-top, 1 nC



# Measurements, summary

> In the all cases reconstructed phase spaces are much wider in the momentum axis than expected from the numerical simulations. 1.5 keV/c momentum resolution is still not sufficient.

> For the small charge of 20 pC and flat-top laser temporal profile the longitudinal structure of the reconstructed longitudinal phase space is in good agreement with the temporal laser profile.

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# Conclusions and outlook

- Two techniques for longitudinal phase space measurements were presented and described.

- First measurements using tomographic technique were performed at PITZ for different bunch charges and various laser temporal profiles.

- Unfortunately, there was no other diagnostic available to compare measurement results. Hope to do it soon…

- This summer the plasma cell will be installed at PITZ. RF deflector will help to perform studies of the bunch energy modulation caused by interaction with plasma.