Longitudinal phase space tomography at the PITZ facility

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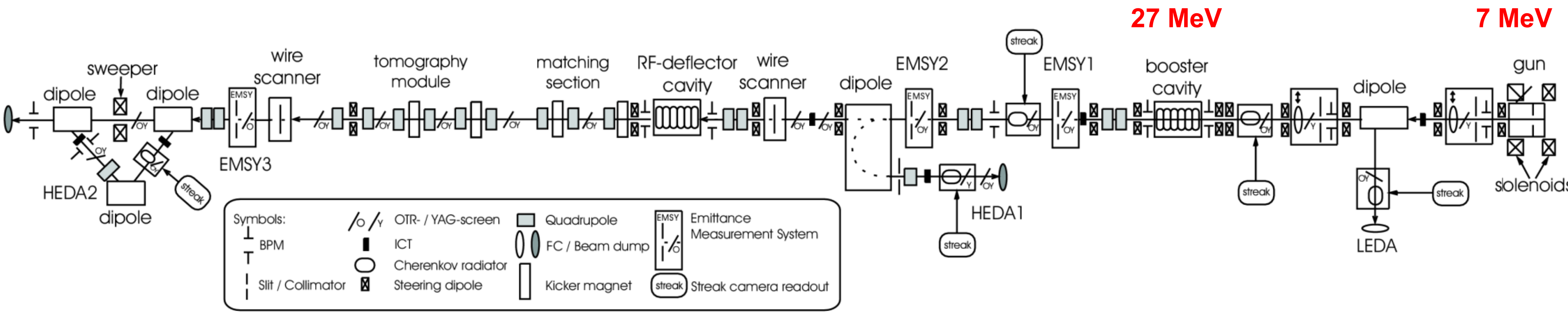
Forschungs seminar SS 2013
Humboldt-Universität zu Berlin
31st of May 2013

HELMHOLTZ
GEMEINSCHAFT

DESY

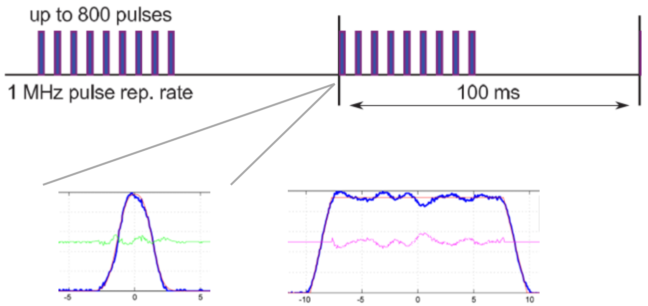
The Photo Injector Test facility, Zeuthen site (PITZ)



PITZ main parameters:

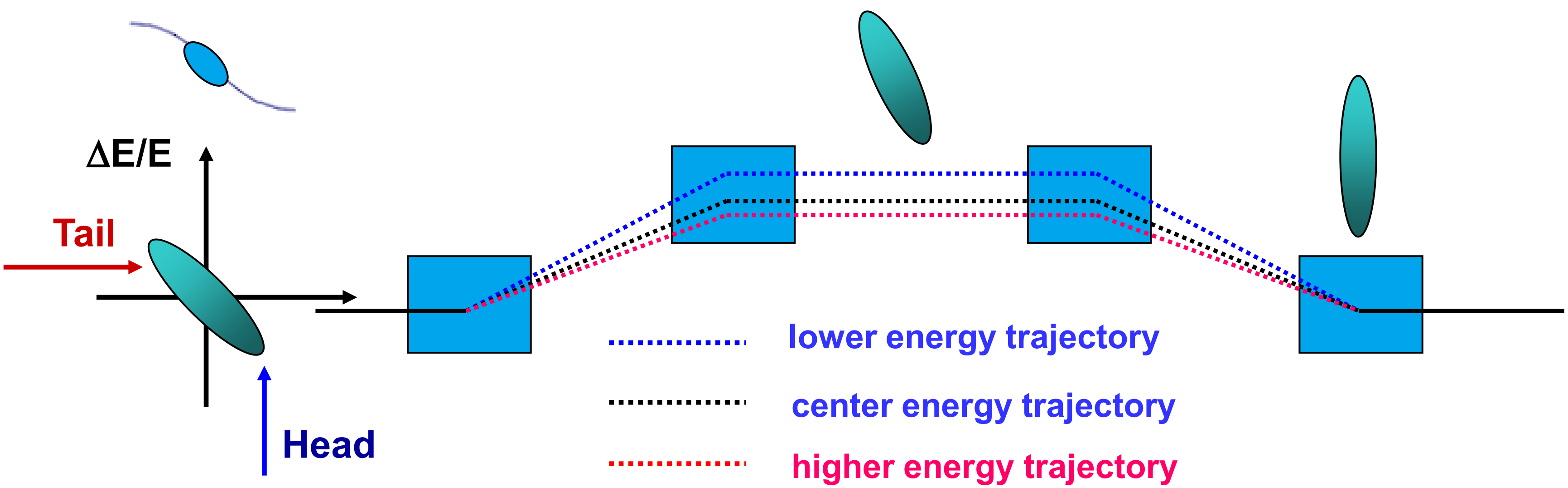
Bunch charge	1 pC … 4 nC
Repetition rate	10 Hz
Beam energy after gun	1 … 7 MeV
Beam energy after booster	1 … 27 MeV
Number of bunches	1 … 800
Bunch spacing	1 us
Laser pulse temporal shape	2 ps Gauss … 22 ps flat-top

Laser pulse train structure



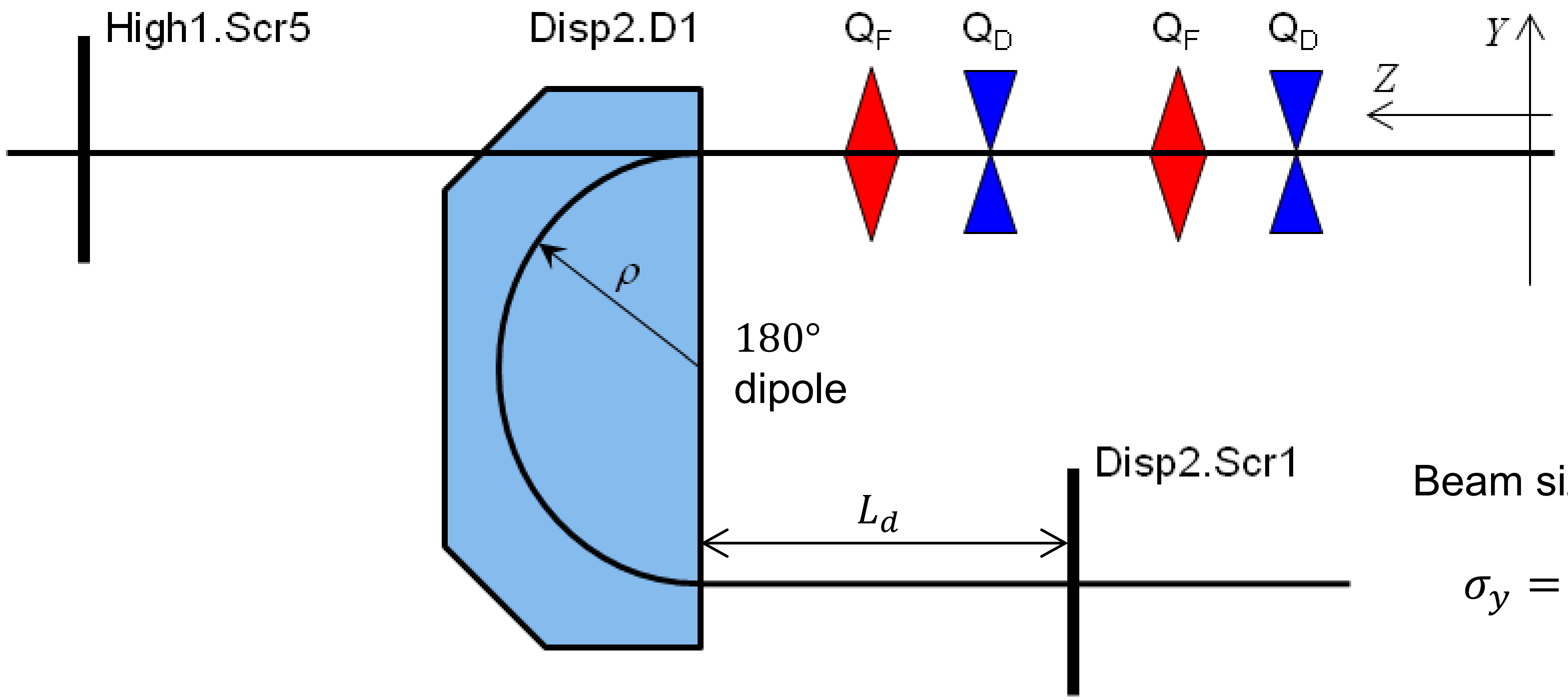
Electron bunch characterization

Characteristic:	Originate from:
Bunch charge	Electron source
Bunch energy	Acceleration
Bunch transverse size	Emittance, transverse phase space
Bunch length	Energy spread, longitudinal phase space



1. Overview of the PITZ facility
2. **High momentum measurements at PITZ**
3. Idea of the tomography
4. Algebraic reconstruction technique (ART)
5. Simulation of measurements in ASTRA
6. Experimental data, reconstruction results
7. Conclusion

HEDA1 momentum measurements



Beam size on screen

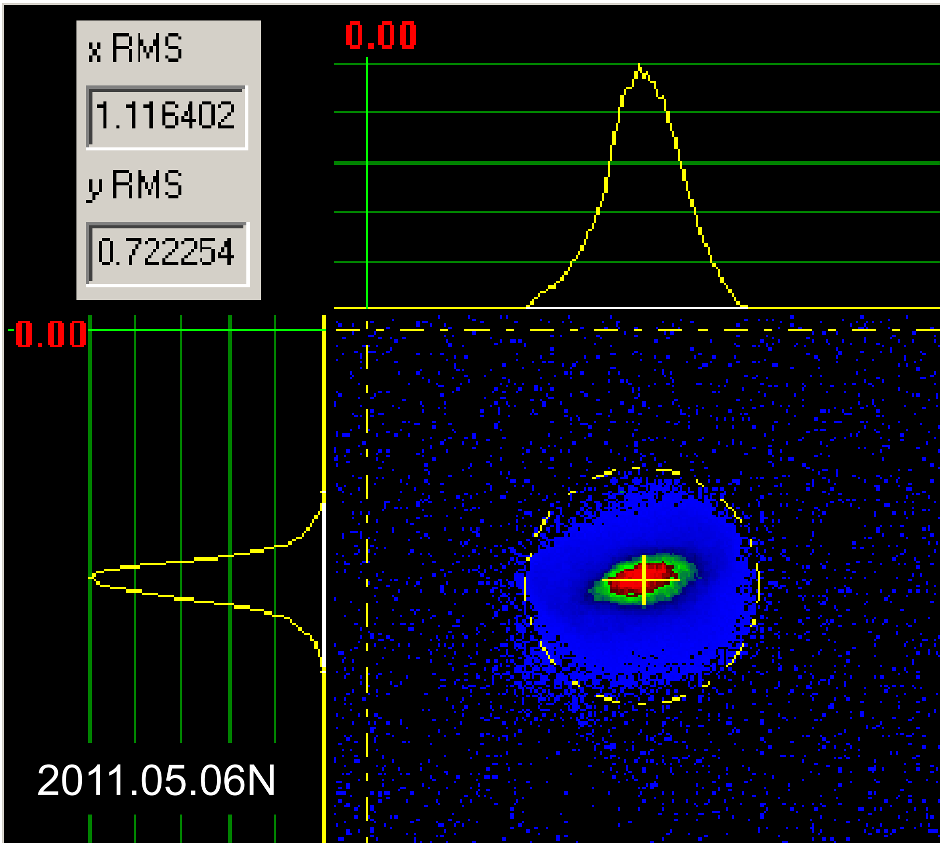
$$\sigma_y = D_y \frac{\Delta p}{p}$$

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

$$D_y = 0.6\ m$$

HEDA1 momentum resolution, standard measurements

High1.Scr5 Yrms = 0.72 mm



$$\sigma_\delta = \frac{\sigma_y}{D_y}$$

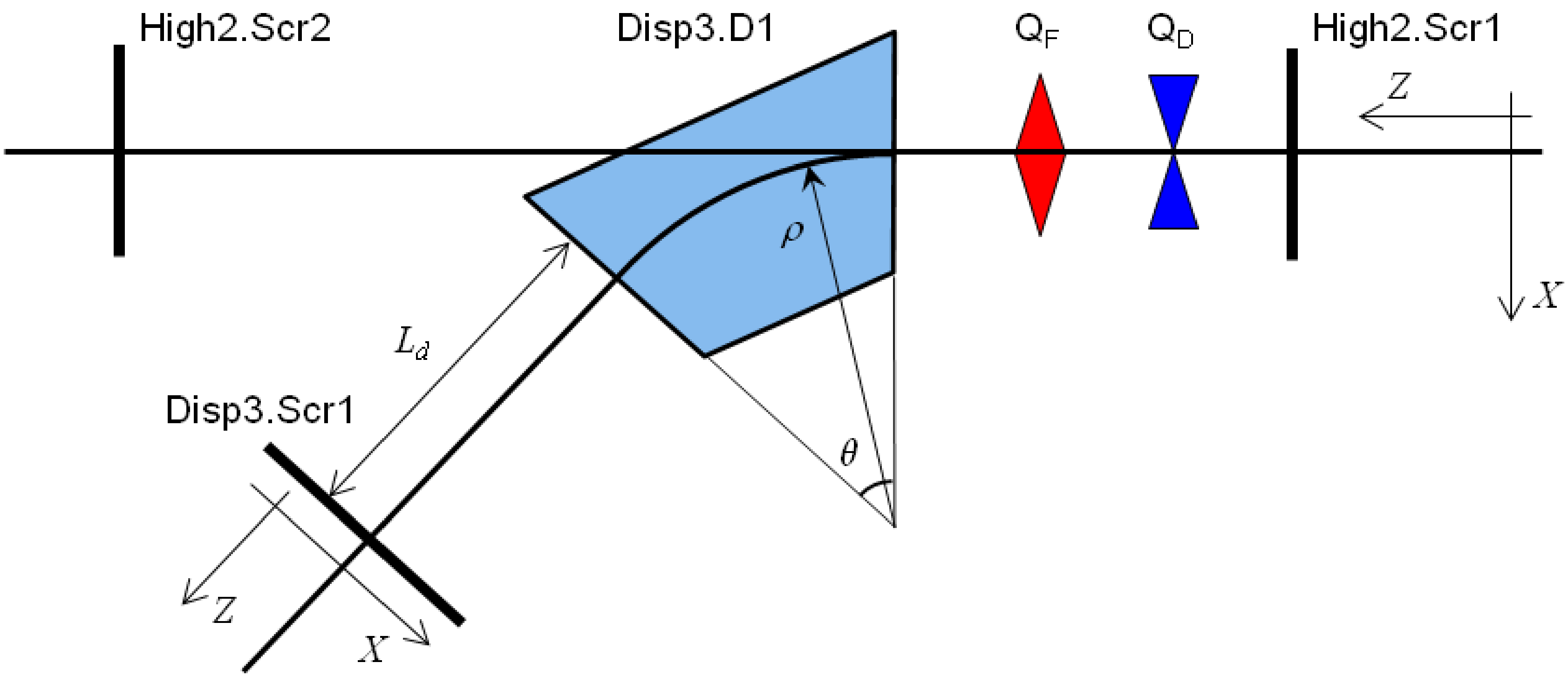
$$D_y = \rho(1 - \cos(\theta)) + L\sin(\theta) = 2\rho$$

$$\rho = 0.3\ m \rightarrow D_y = 0.6\ m$$

$$\sigma_\delta = \frac{0.72 \cdot 10^{-3}}{0.6} = 1.2 \cdot 10^{-3}$$

For 25 MeV/c beam → 30 keV/c

HEDA2 momentum measurements

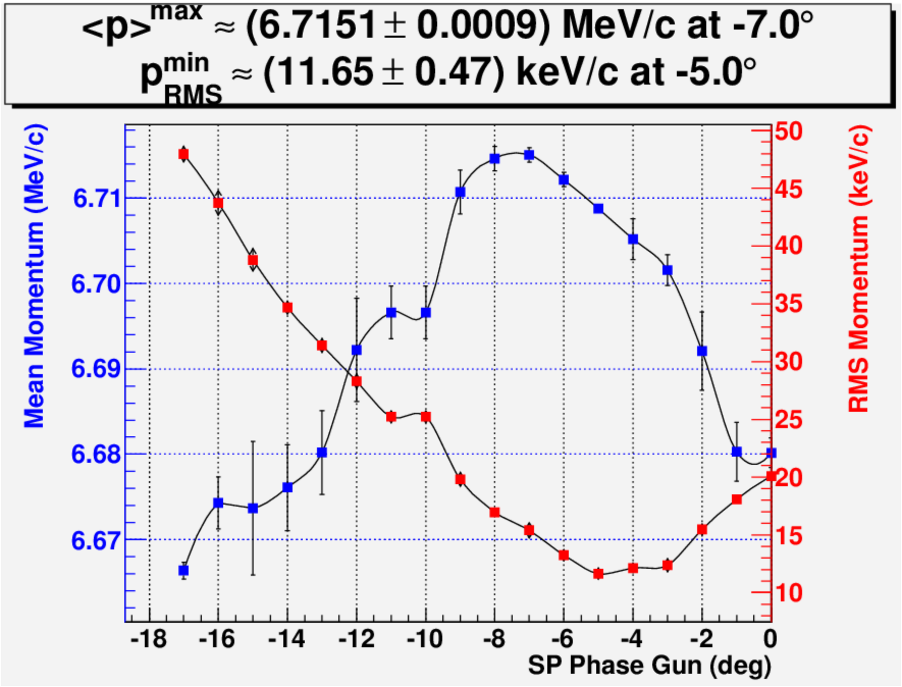


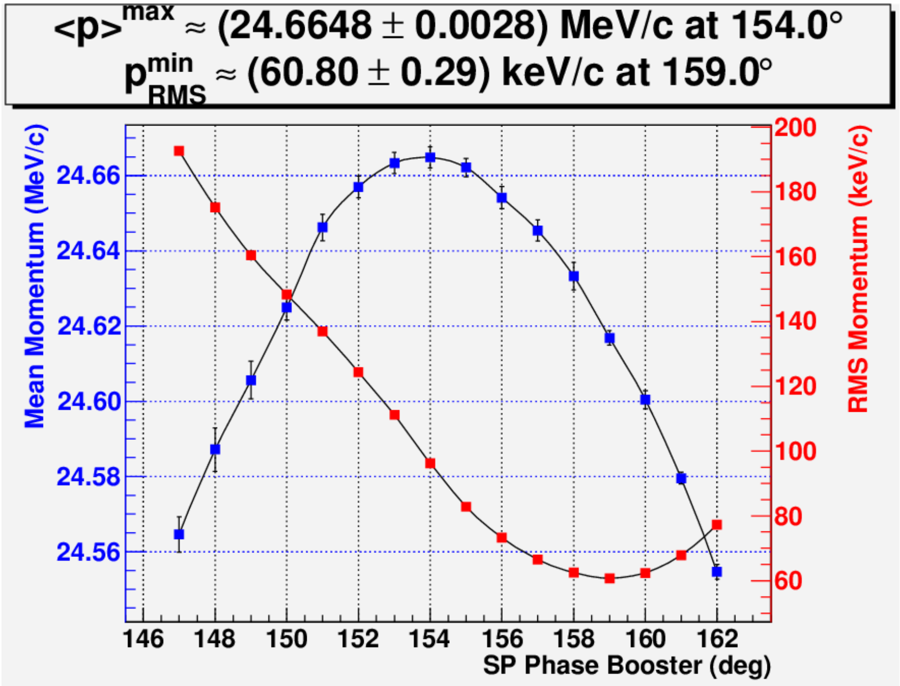
$$D_x = \rho(1 - cos(\theta)) + L_d sin(\theta), \qquad \theta = 60°$$

$$\sigma_x = D_x \frac{\Delta p}{p}$$

$$D_x = 0.9\ m$$

LEDA and HEDA1 momentum phase scans, 2011.05.06N





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

Electron bunch mean momentum after the booster

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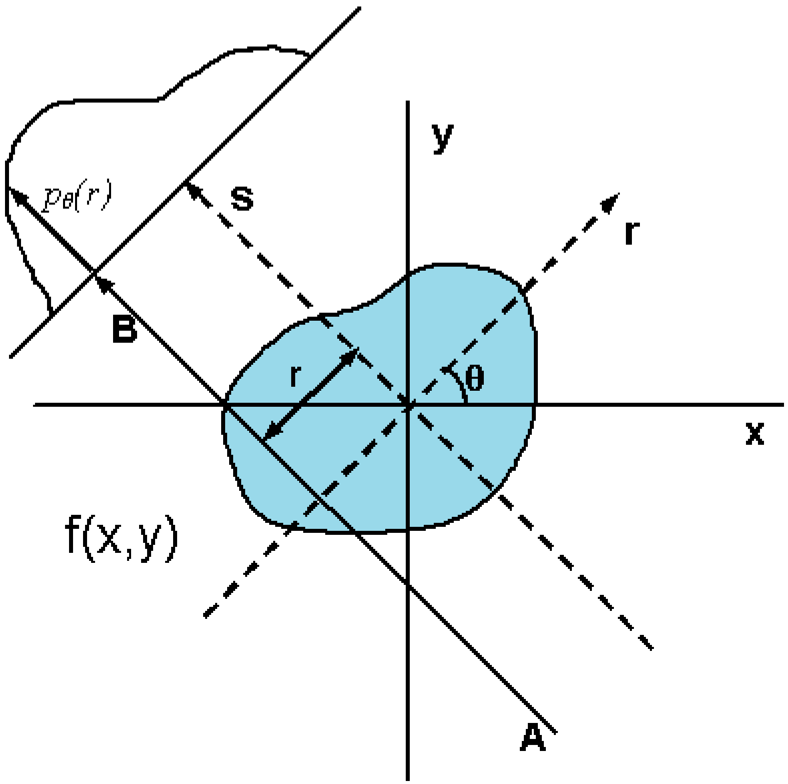
Tomography



We have unknown object $f(x, y)$.

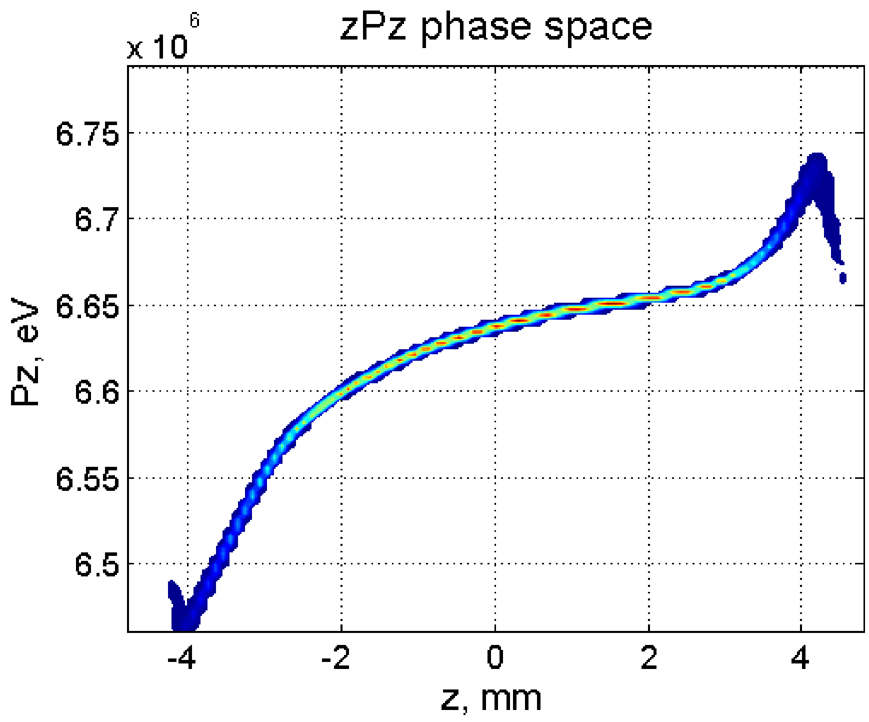
We can measure projection of this object $p_\theta(r)$ at different angle θ. This is called tomography transformation.

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

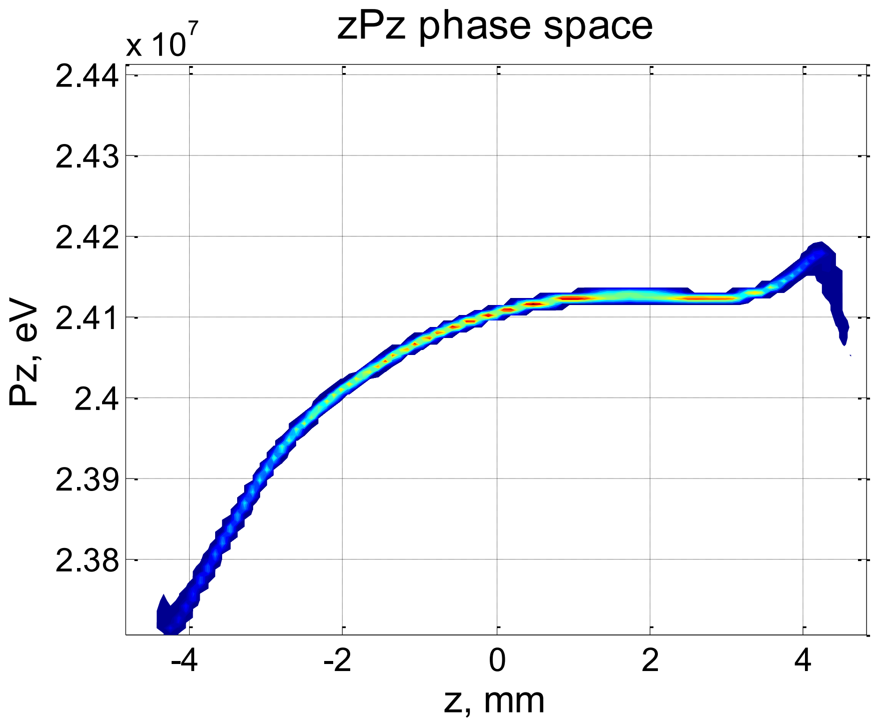
This procedures can be applied to the longitudinal phase space image.

Longitudinal phase space, 1 nC simulation

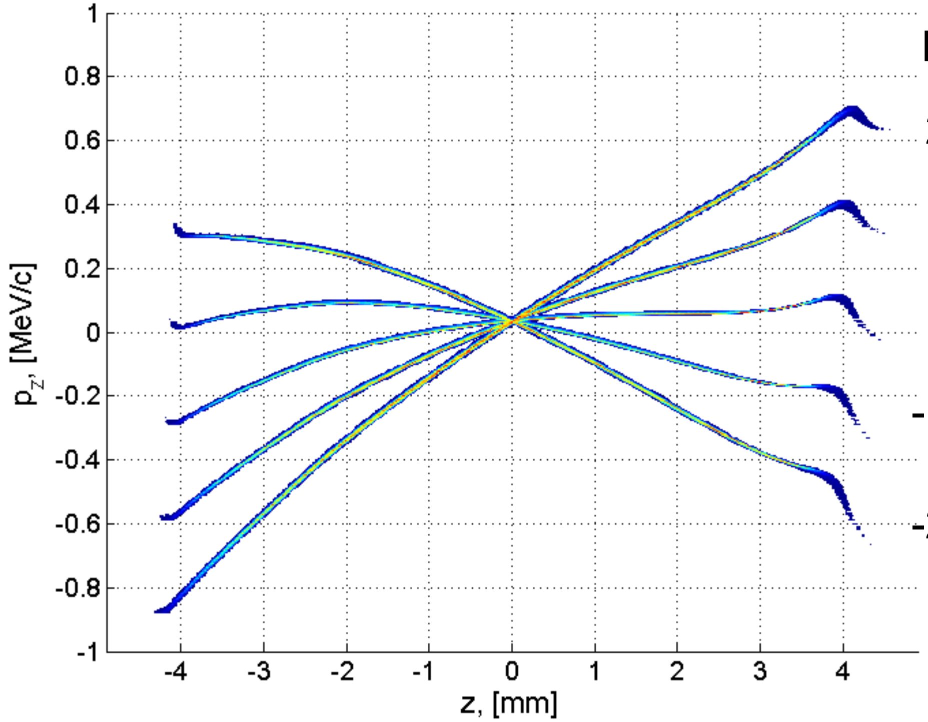
After gun (phase 0)



After booster (phase 0)



Simulated longitudinal phase spaces, 1 nC charge



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

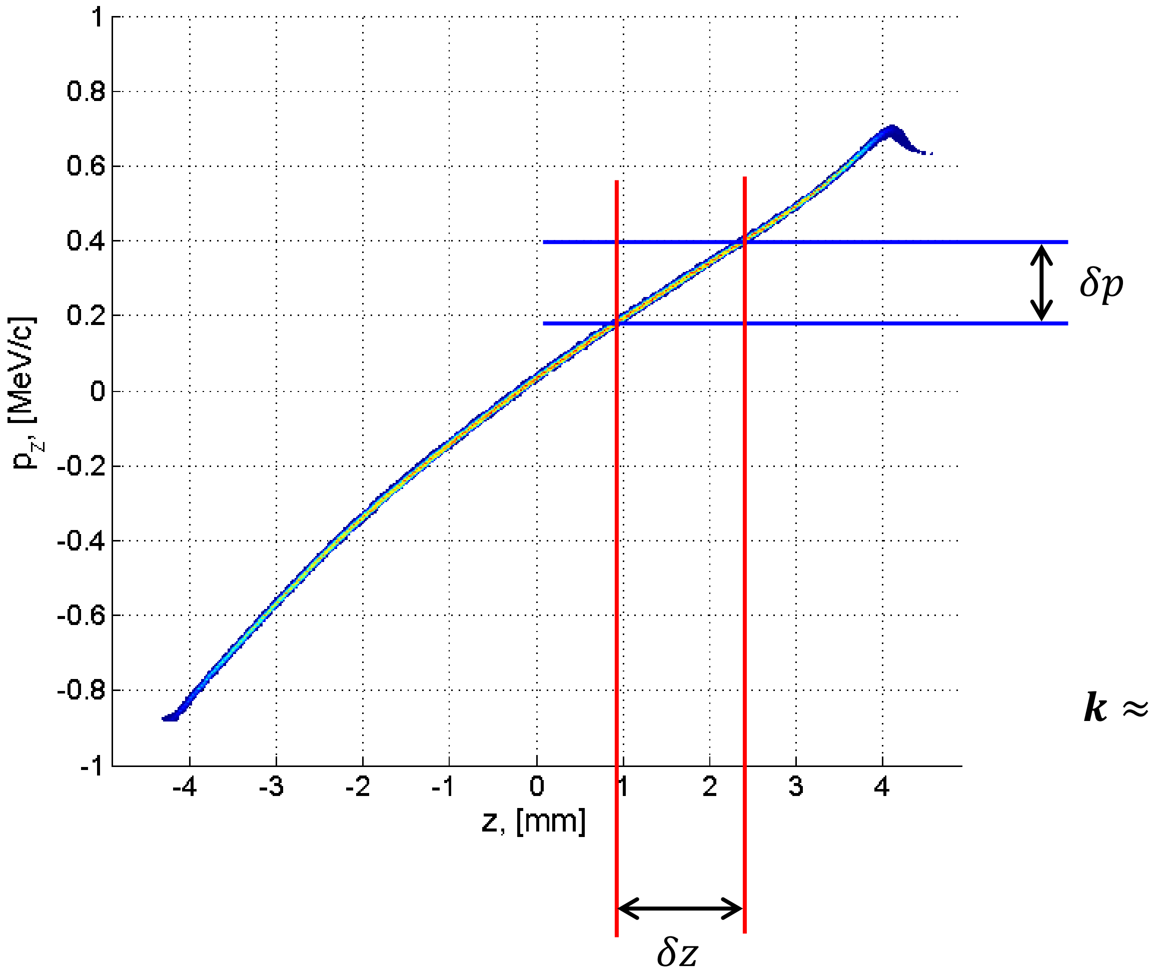
$$p = 6.7 Mev/c + 18 Mev/c \cdot cos(\varphi)$$

Electron bunch mean momentum after the booster

$$\Delta p_z \approx +147 \frac{keV/c}{ps} \cdot sin(\varphi_0) \cdot \frac{\Delta z}{c}$$

Particle momentum gain by the booster relative to the mean momentum. Particle has position Δz within the bunch.

Longitudinal resolution estimation



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

$$\boldsymbol{k \approx +147\frac{keV/c}{ps} \cdot sin(\varphi_0) \cdot \frac{1}{c}}$$

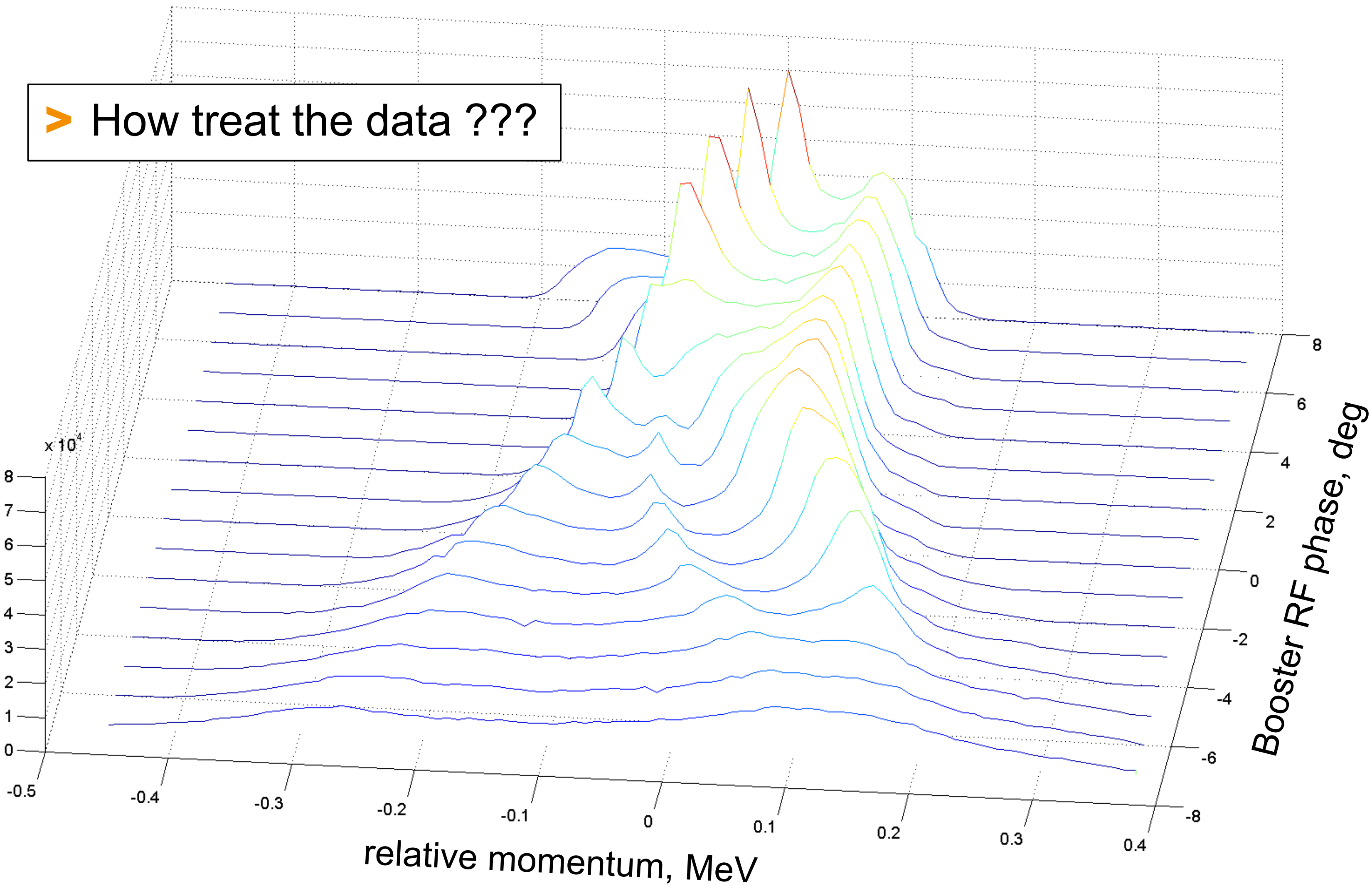
Estimation of longitudinal resolution

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

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

3 keV/c momentum resolution + 2 keV/c slice momentum spread → **0.1 ps resolution ???**

Tomographic reconstruction



Pros and cons

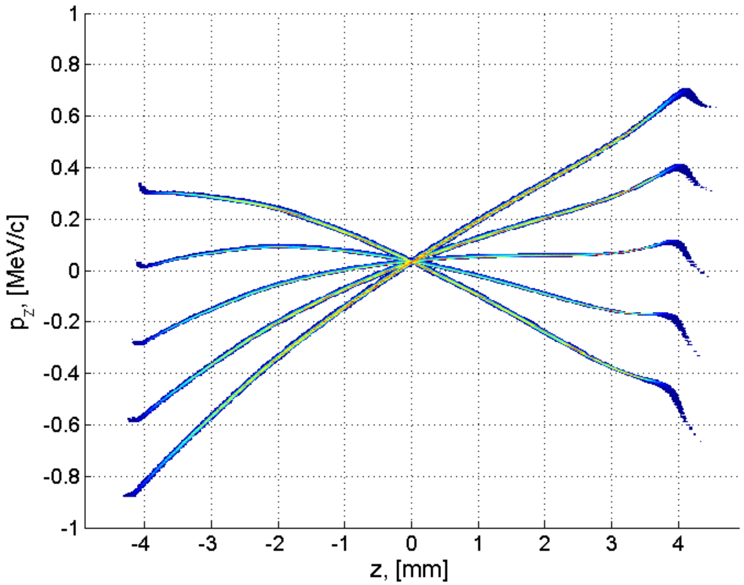
Pros:

- Simple measurements via momentum phase scan
- Quite high temporal resolution*

  * 0.1 ps resolution ???

Cons:

- Sophisticated data treatment
- Not include 90° rotation



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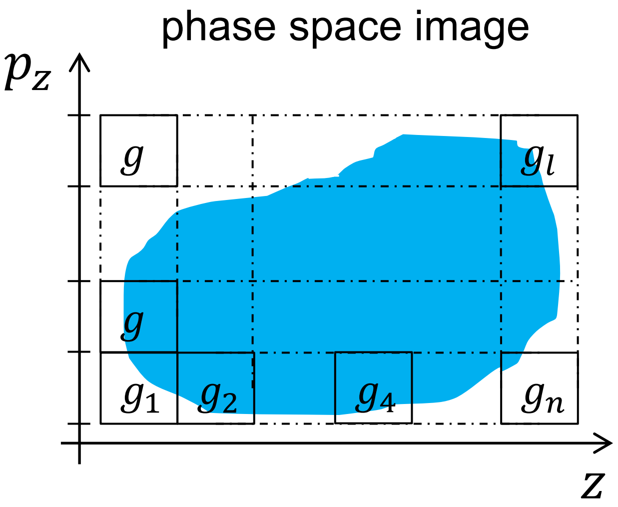
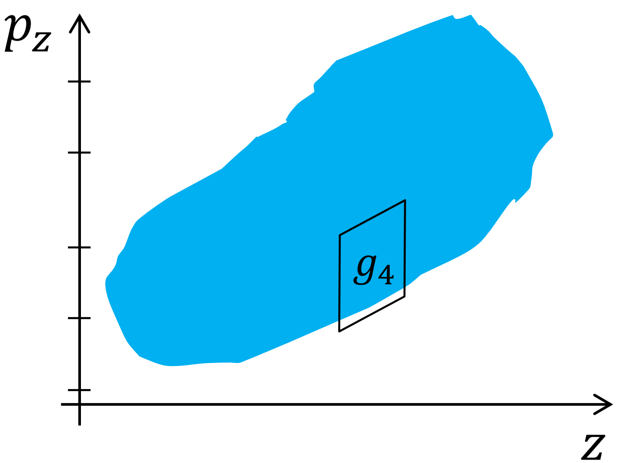
Reconstruction algorithm (ART)

1. Represent 2D image as 1D array – g_l



2. Represent phase space rotation via a_{ijl} matrix

$$p_z(z) = p_z(z) + k(\varphi) \cdot z$$



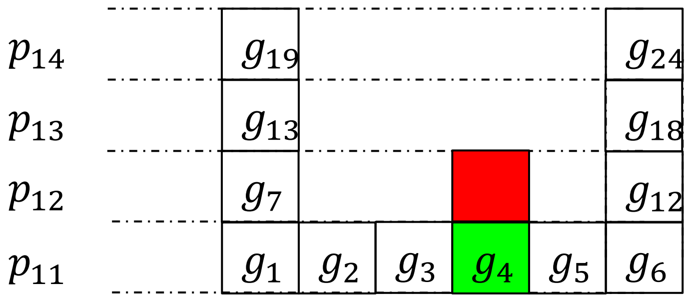
$$p_{ij} = a_{ijl} \cdot g_l$$

i – phase (rotation)

j – momentum bin

l – image pixel index

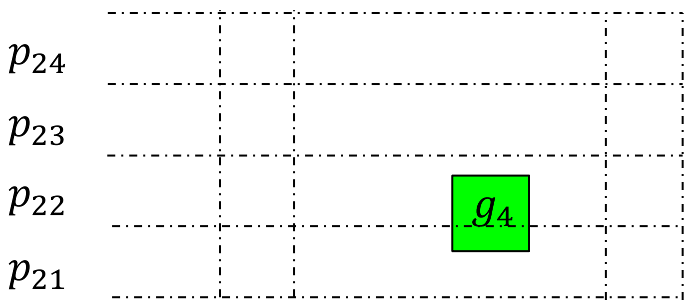
Reconstruction algorithm, filling "a_{ijl}" array



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

$$p_z(z) = p_z(z) + k(\varphi) \cdot z$$

If φ_1 mean no rotation applied then $a_{1,1,4} = 1,\ a_{1,2,4} = 0$



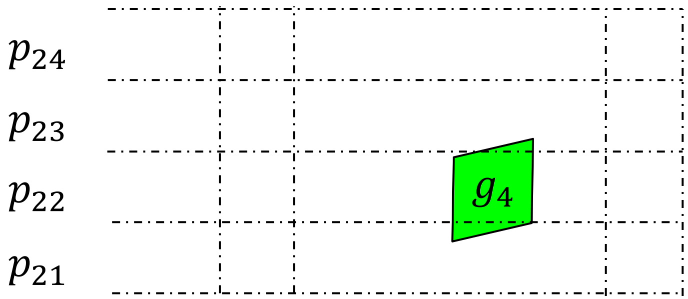
If φ_2 mean rotation applied then $a_{2,1,4} = 0.3,\ a_{2,2,4} = 0.7$

Reconstruction algorithm, filling “a_{ijl}” array

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

$$p_z(z) = p_z(z) + k(\varphi) \cdot z$$

more precise representation:



$$a_{2,1,4} = ???,\ a_{2,2,4} = ???,\ a_{2,3,4} = ???$$

Reconstruction algorithm, iterations

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

i – phase (Nphase)

j – momentum (Npz)

– z coordinate (Nz)

q, l – image index (Nl = Npz*Nz)

k – iteration number

Total calculation time is ~

Npz*Nz*Nphase*Npz*(Npz*Nz + Npz*Npz*Nz) =

= $Npz^3 Nz^2$Nphase(1 + Npz) =

= $Npz^4 Nz^2$Nphase

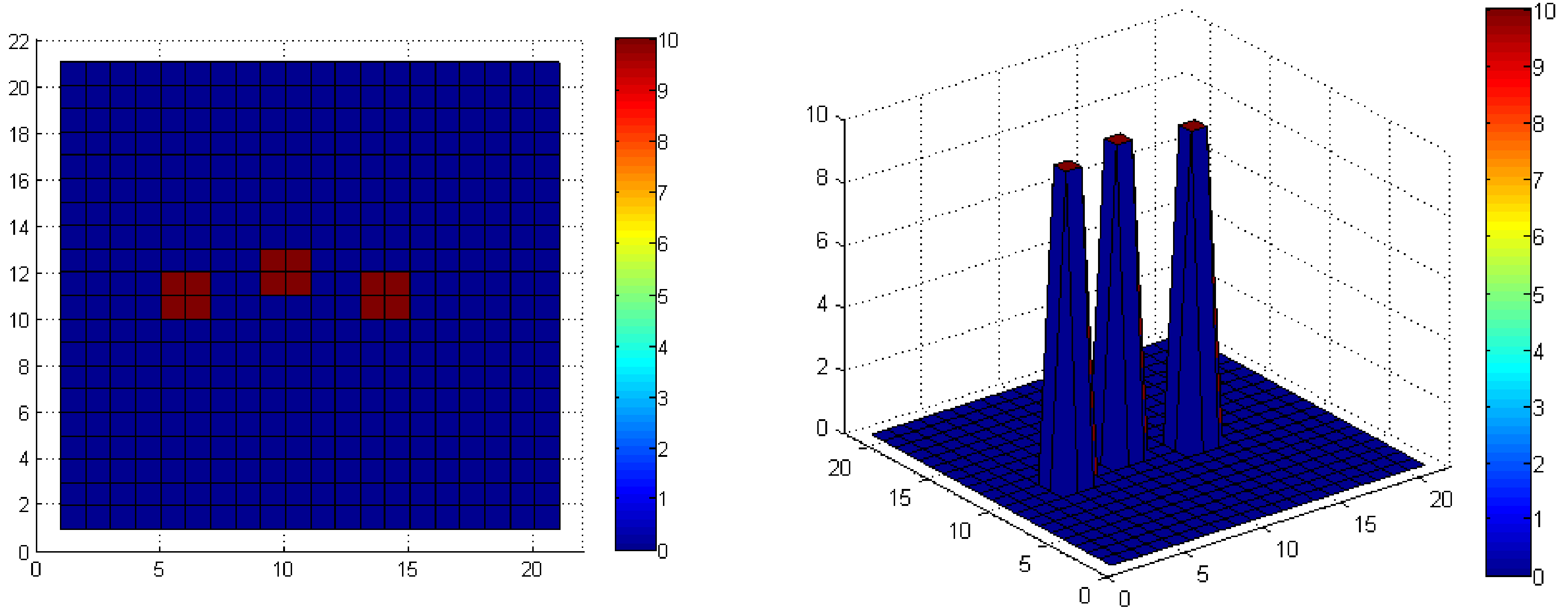
Convergence criteria

$$C(k) = \sqrt{\frac{\sum_q \left(g_q^{(k)} - g_q^{(k-1)}\right)^2}{q_{max}}} \Big/ max(g^{(k)}),$$

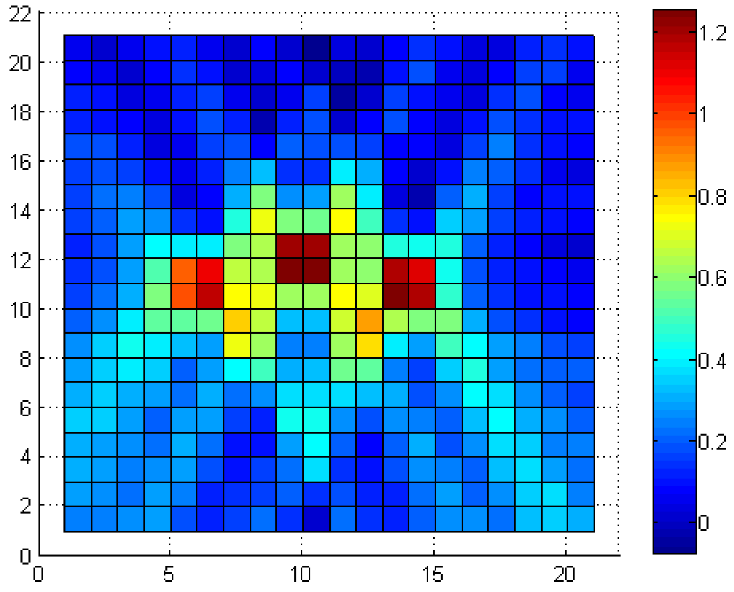
where q_{max} and $max(g^{(k)})$ are number of elements and maximal element in the reconstructed image $g^{(k)}$ respectively.

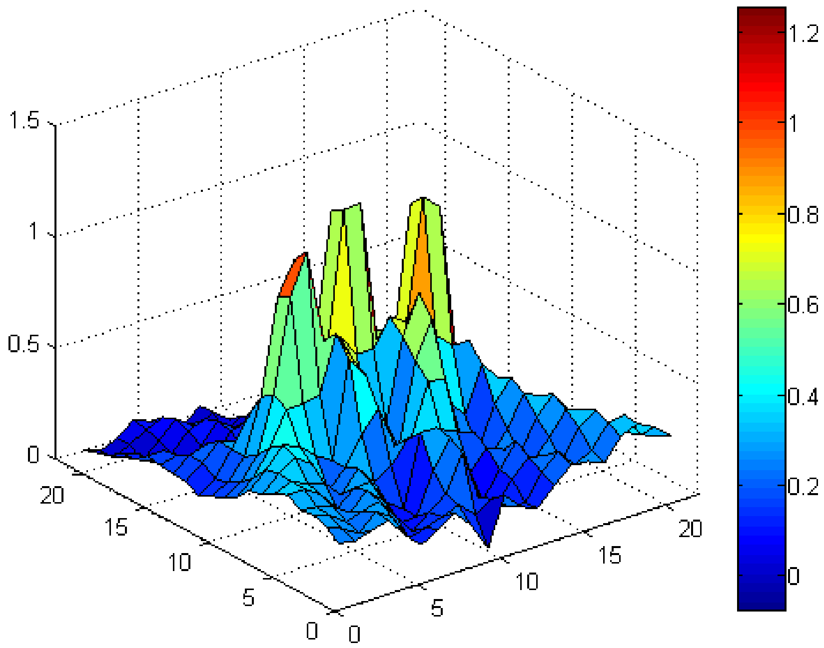
When $C(k)$ becomes less than 10^{-3} we can stop iterations.

Simple reconstruction example, initial image

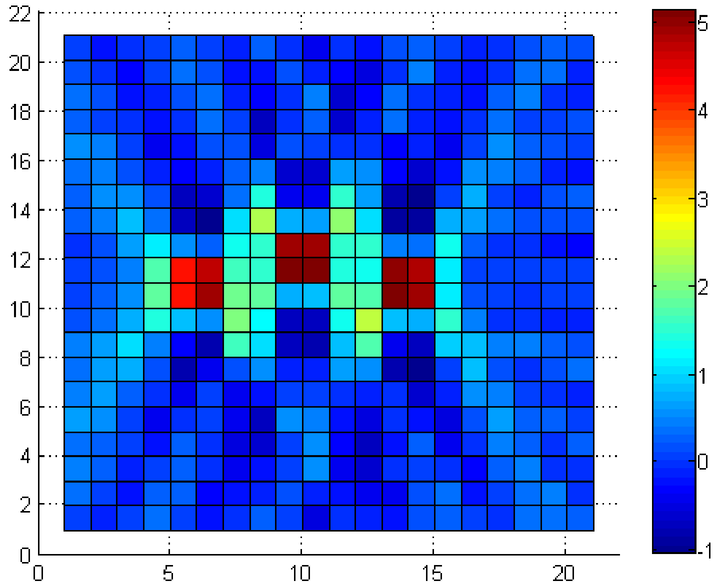


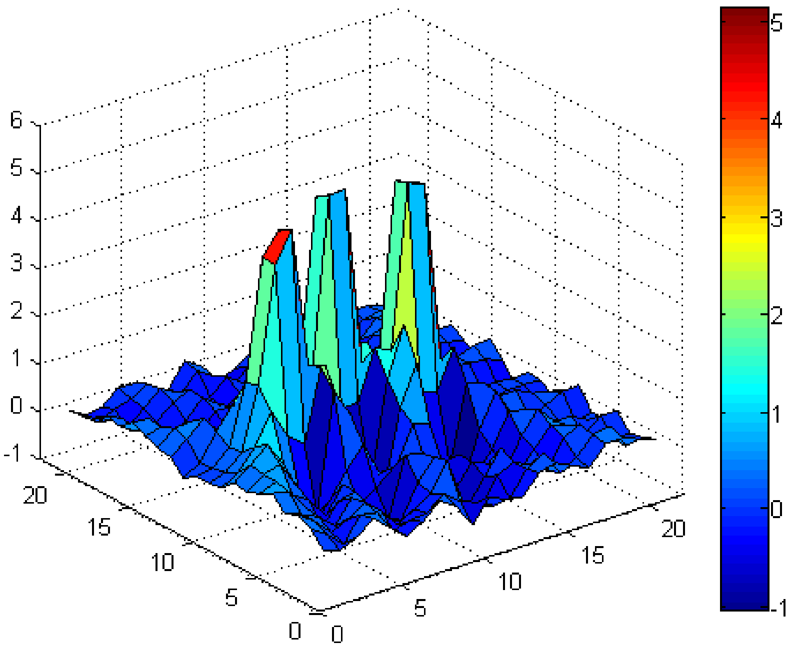
Reconstructed image, 1 iteration



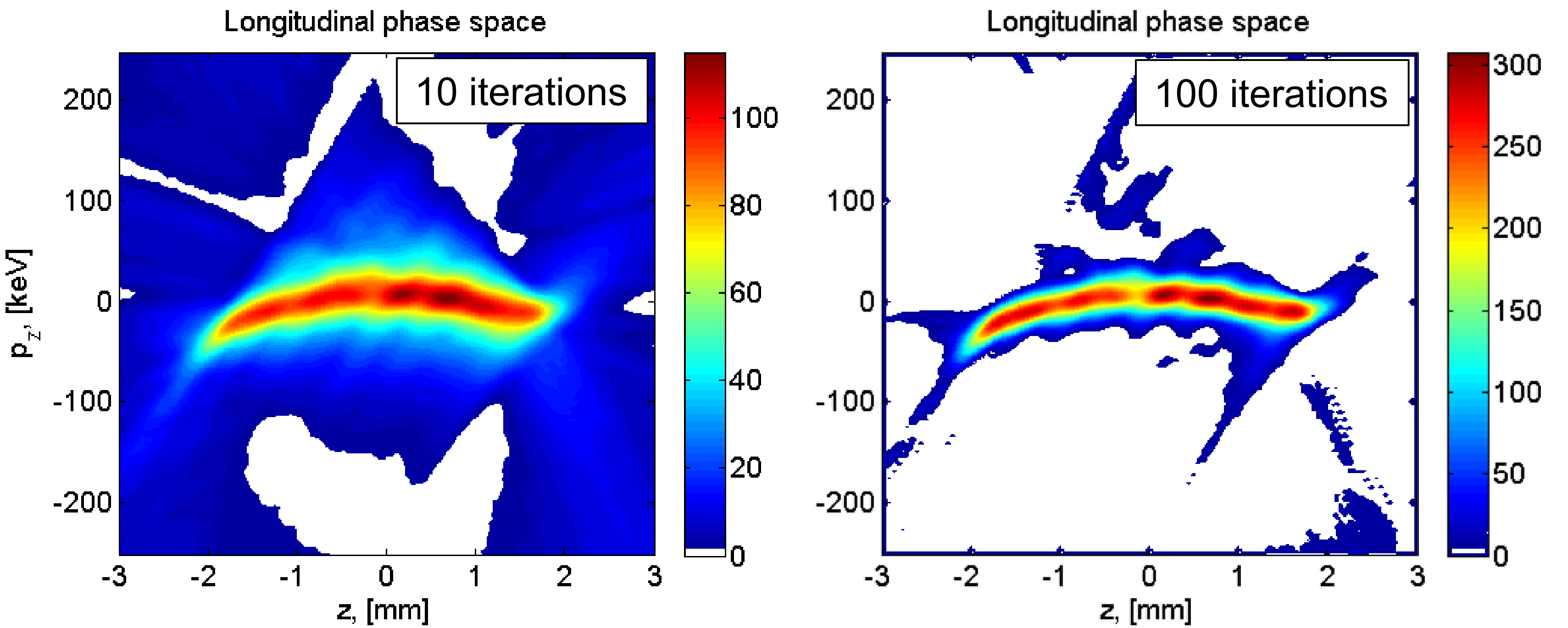


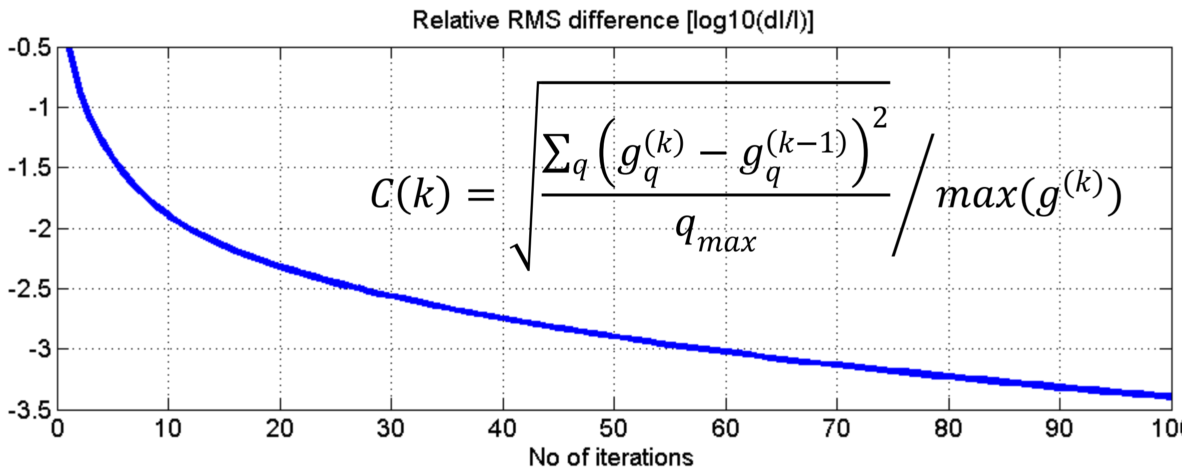
Example, 10 iteration





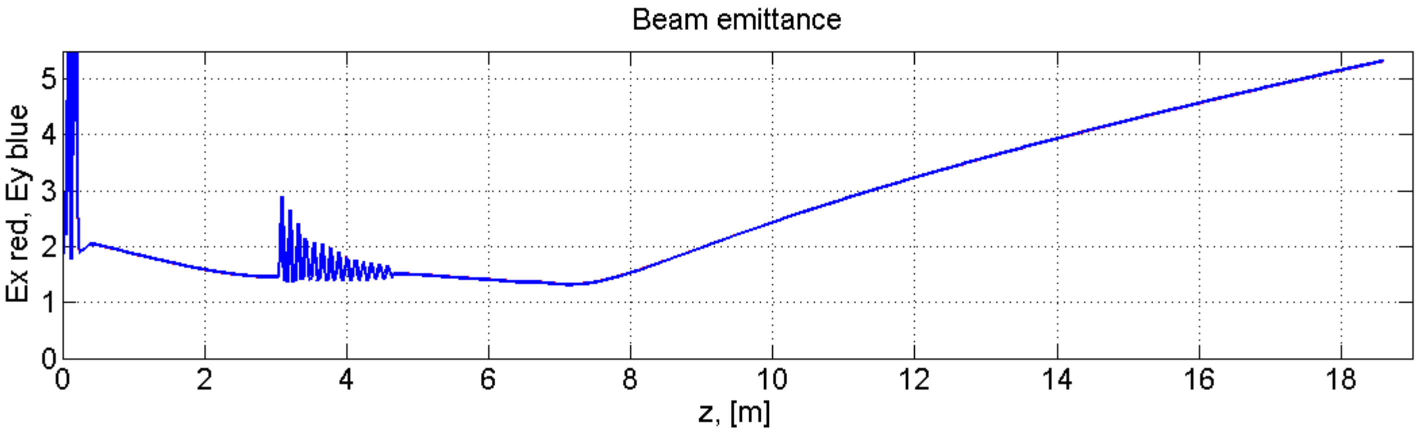
Convergence

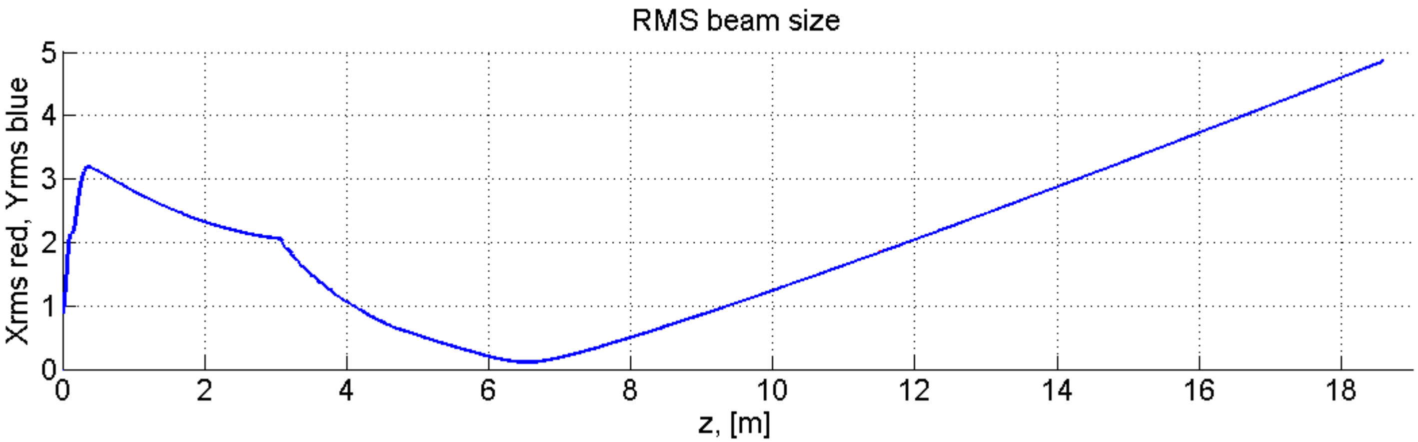




$$C(k) = \sqrt{\frac{\sum_q \left(g_q^{(k)} - g_q^{(k-1)}\right)^2}{q_{max}}} \Big/ max(g^{(k)})$$

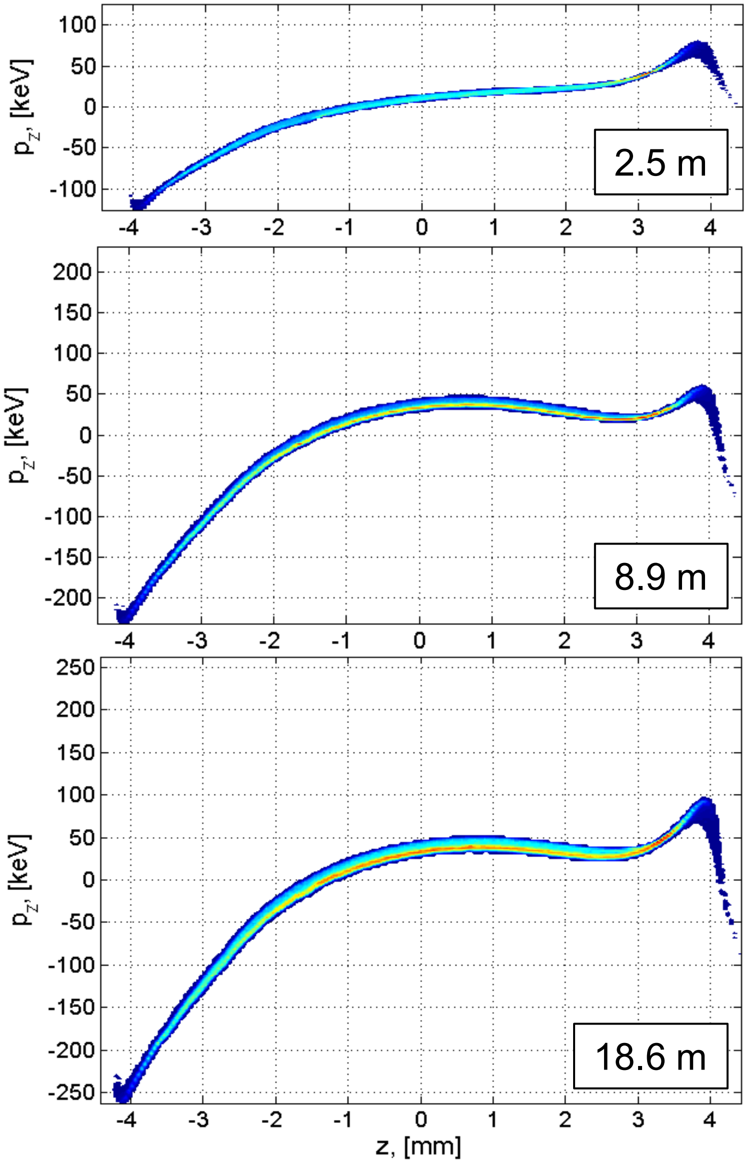
ASTRA initial parameters





Charge	1 nC
Laser	17.5 ps
BSA	0.4 mm
Main	377 A
Gun	6.68 MeV/c
Booster	22.4 MeV/c

Beam transport and phase spaces along beamline



Charge	1 nC
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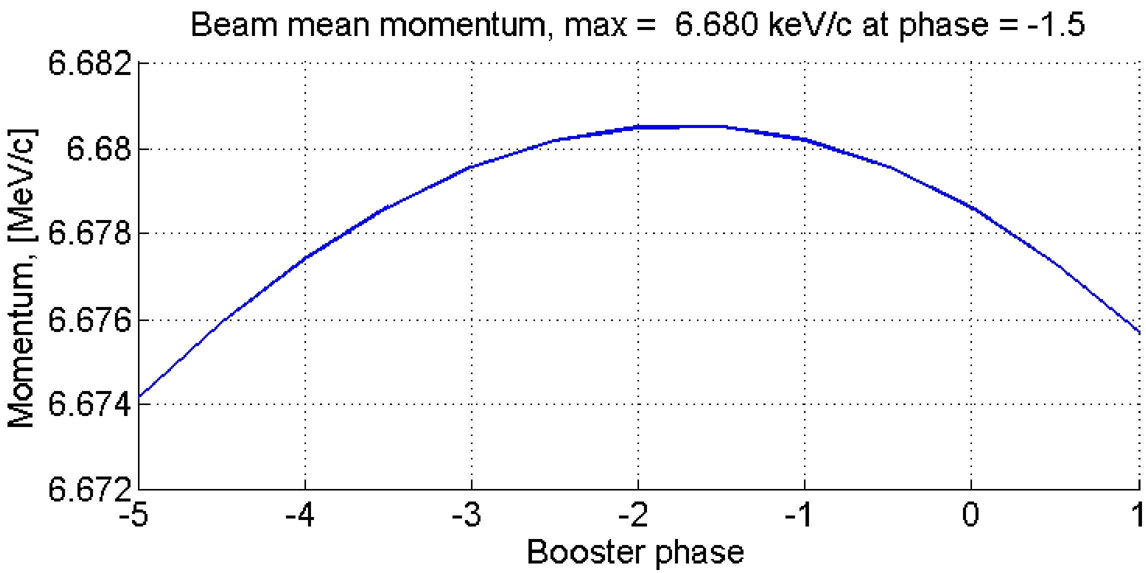
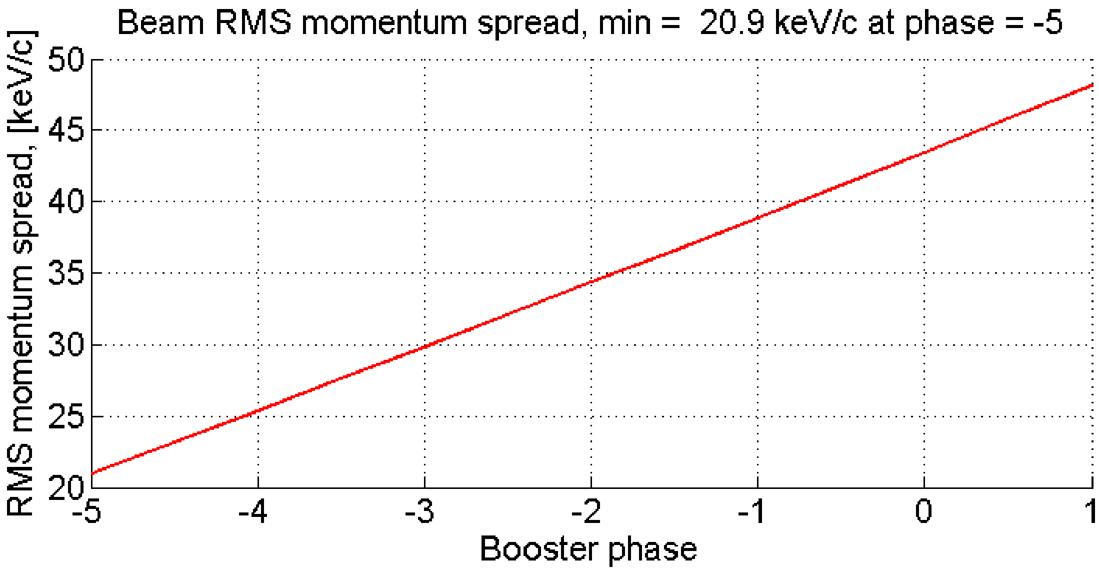
Momentum phase scan, gun





Charge	1 nC
Laser	17.5 ps
BSA	0.4 mm
Main	377 A
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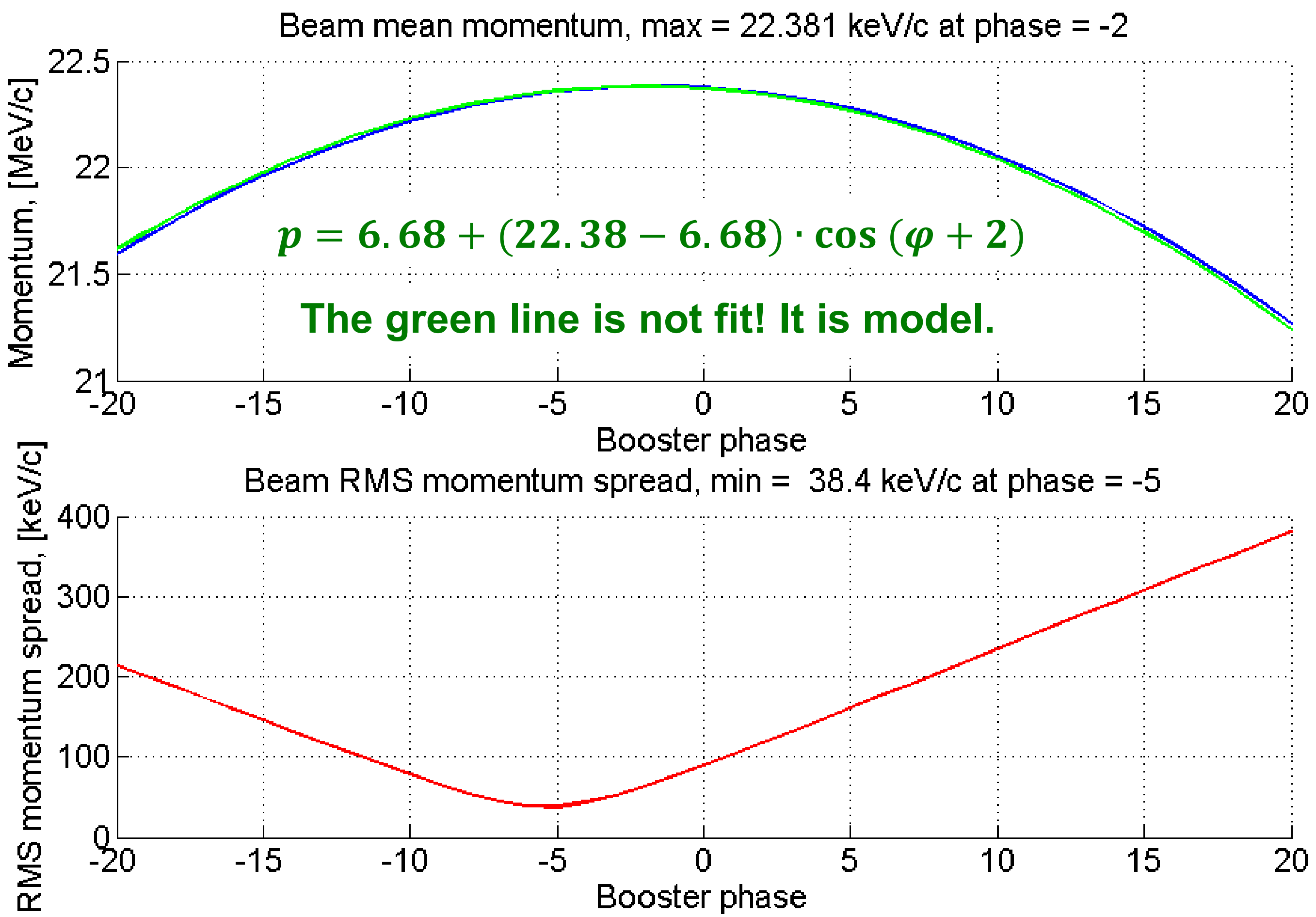
Momentum phase scan, booster



Charge	1 nC
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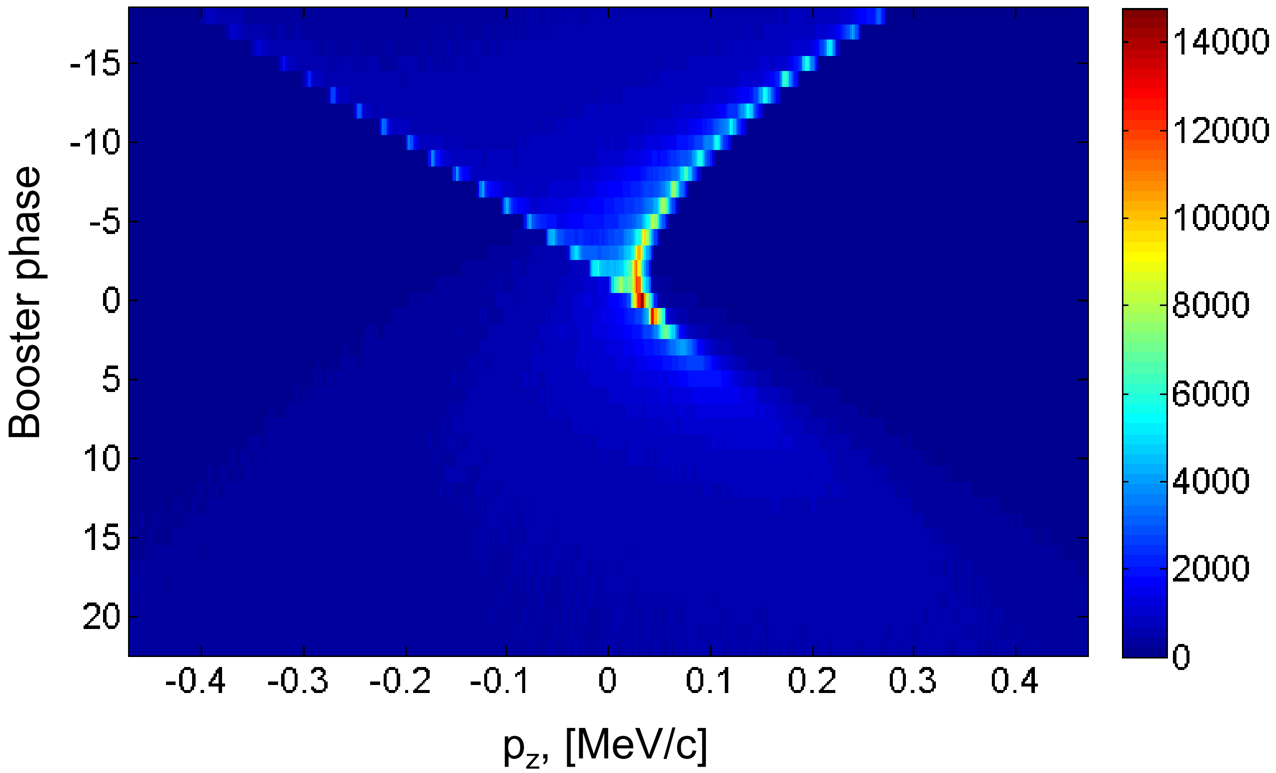
Initial data for reconstruction



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BSA	0.4 mm
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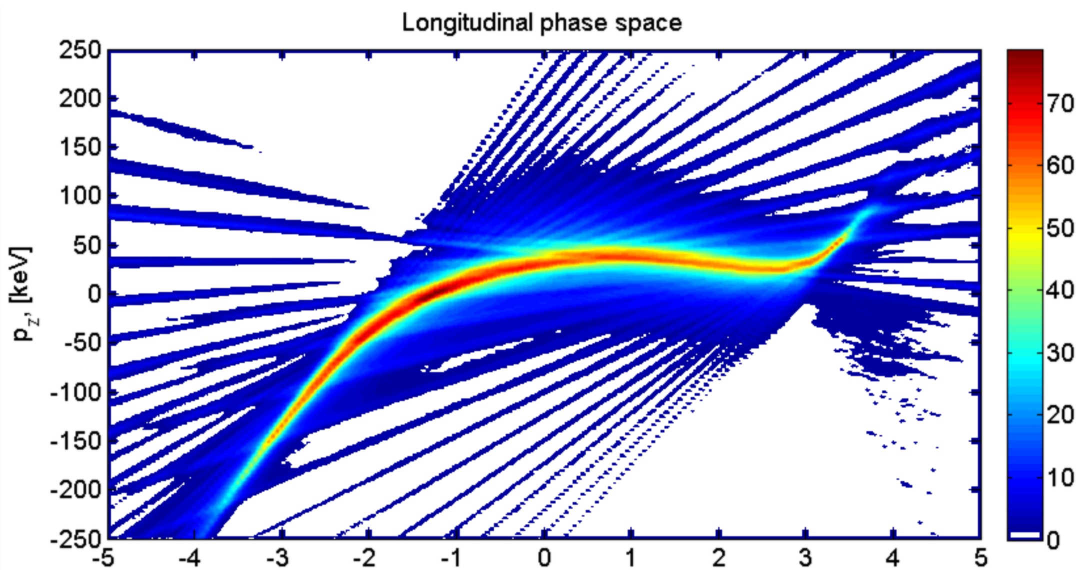
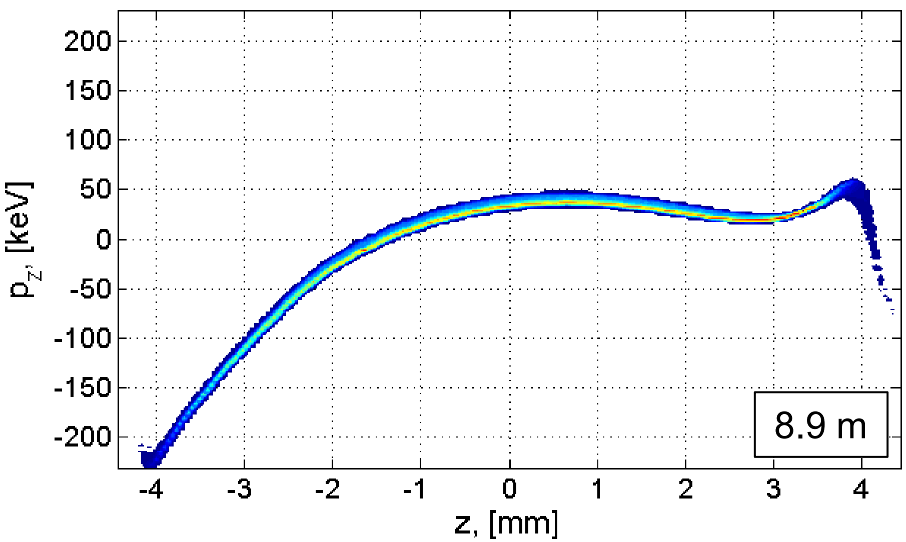
ART reconstruction (ASTRA data)



Reconstructed longitudinal phase space
100 iterations

Charge	1 nC
Laser	17.5 ps
BSA	0.4 mm
Main	377 A
Gun	6.68 MeV/c
Booster	22.4 MeV/c



ASTRA
longitudinal phase space

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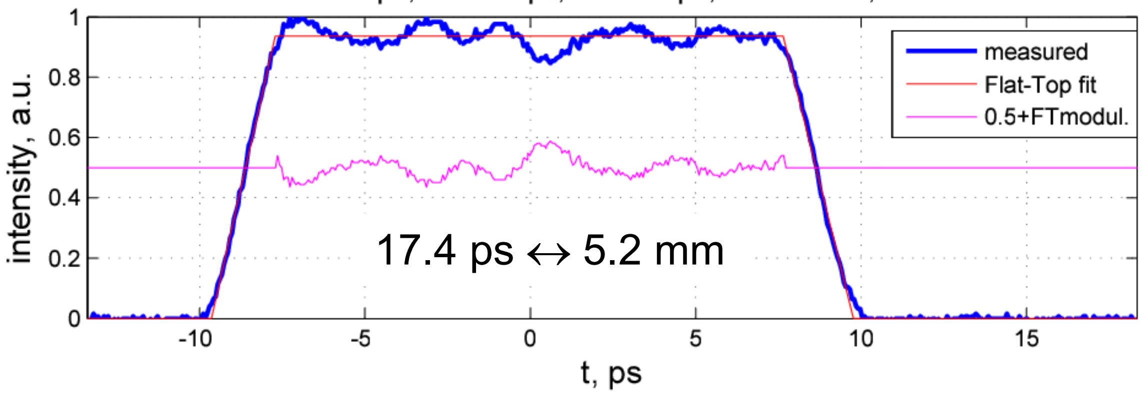
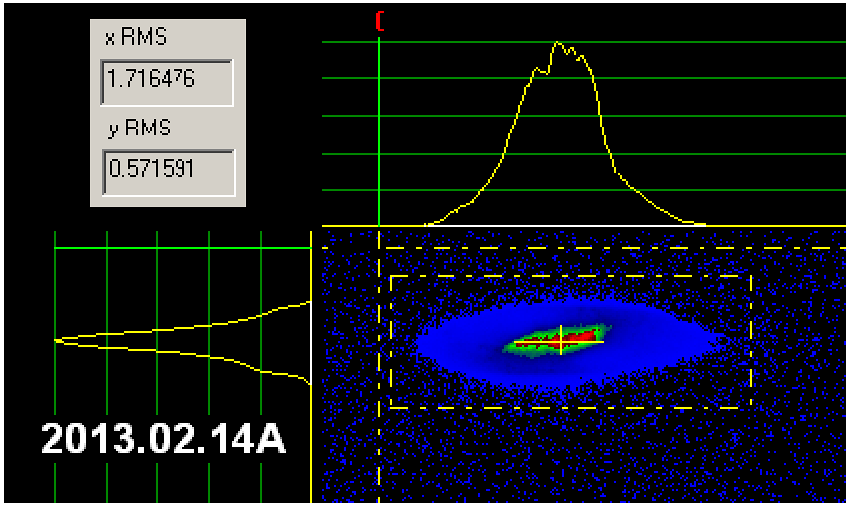
Experimental data, machine parameters, setup I

Laser temporal profile



Charge	1 nC
Laser	17.4 ps
BSA	0.4 mm
Main	377 A
Gun	6.68 MeV/c
Booster	22.4 MeV/c

HEDA1 reference screen

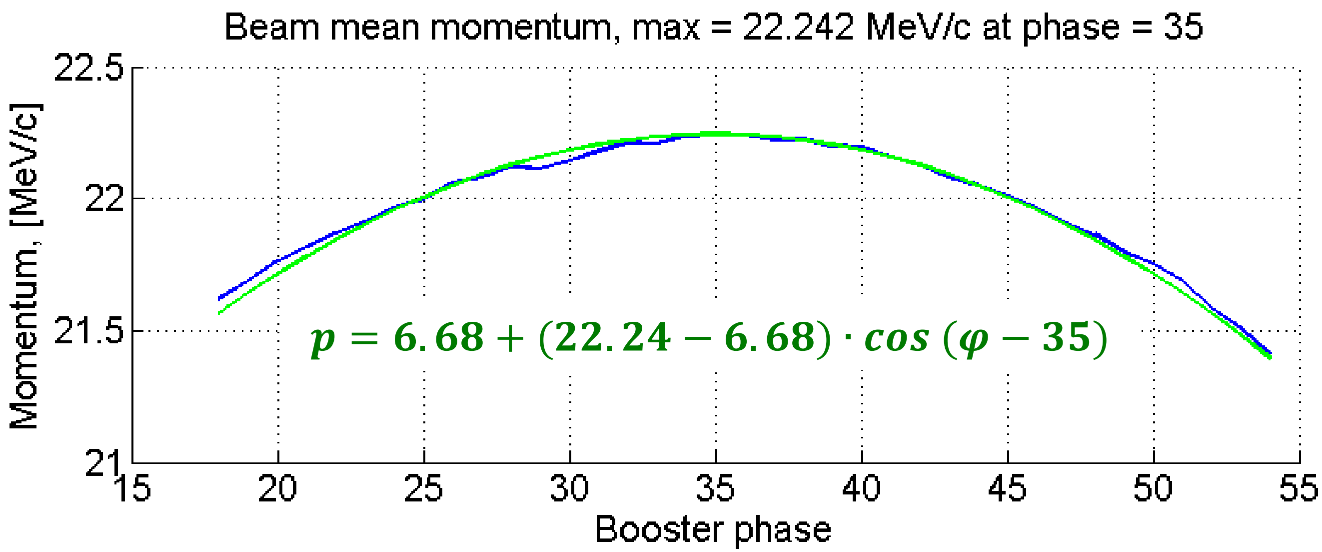


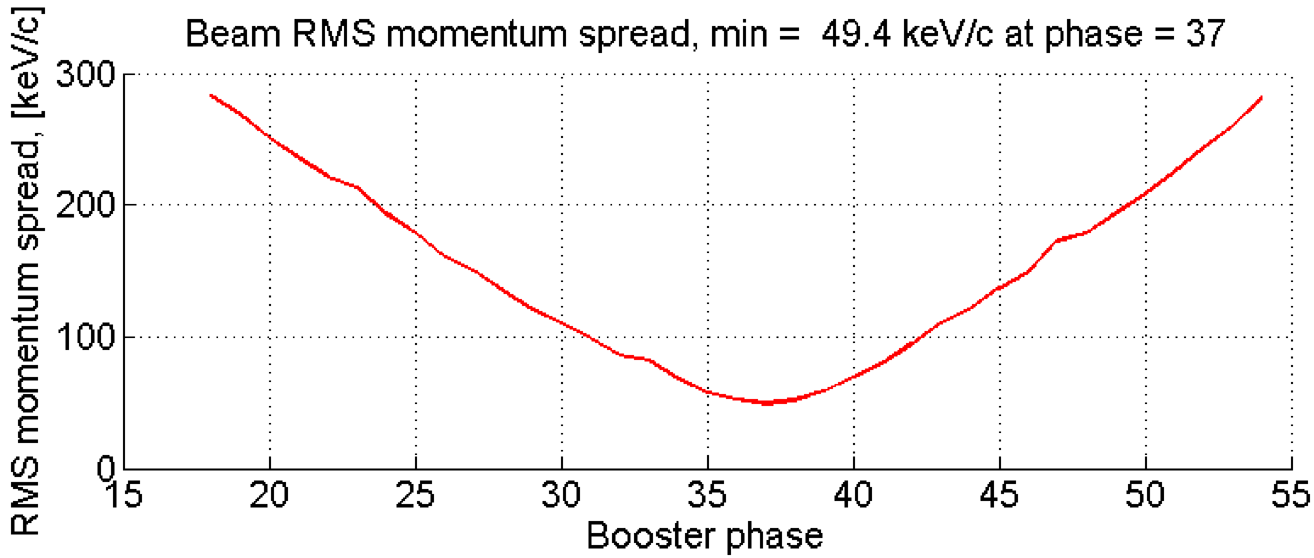
Momentum resolution:

$$\sigma_\delta = \frac{0.57 \cdot 10^{-3}}{0.6} = 0.95 \cdot 10^{-3}$$

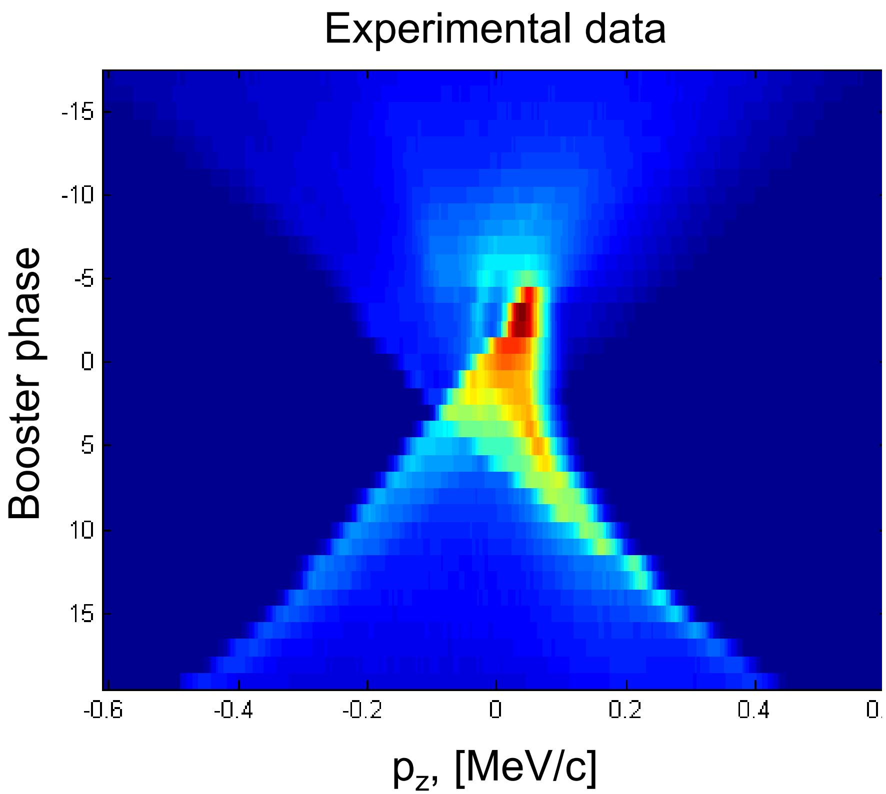
For 22.2 MeV/c beam → 21 keV/c

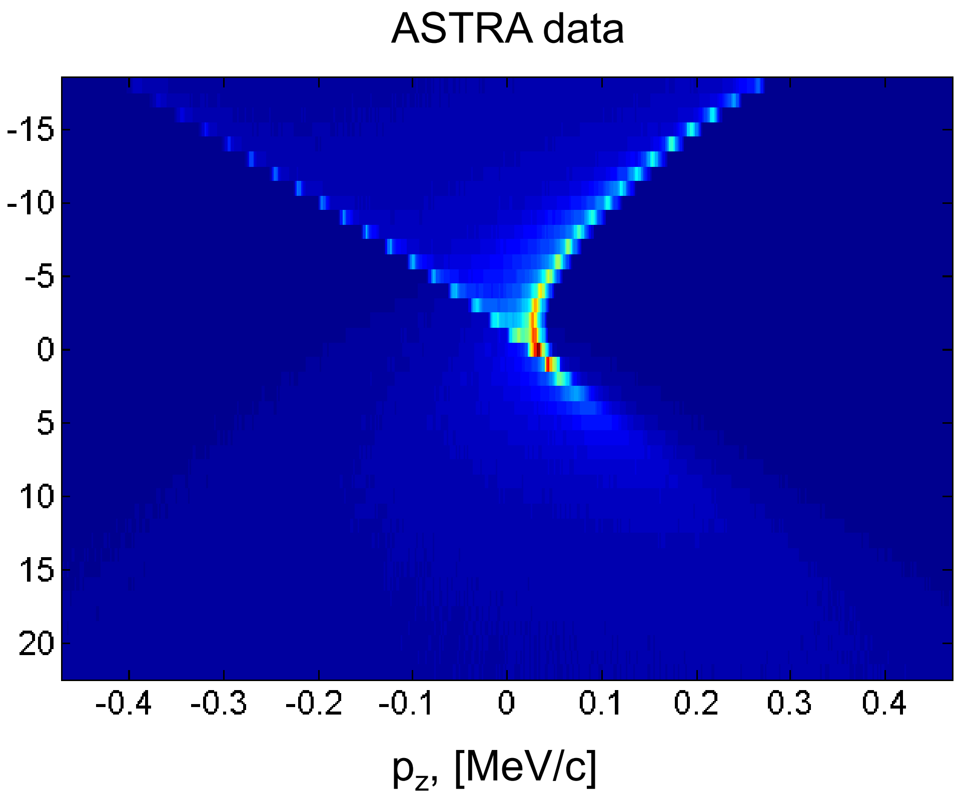
Data from 14.02.2013 19:27:18, HEDA1 momentum scan



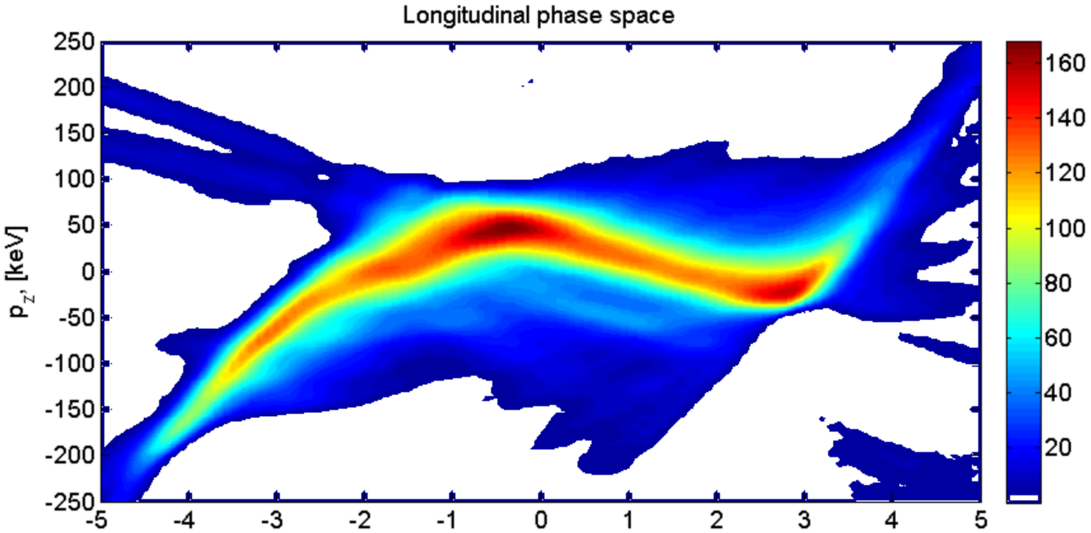


Initial data for reconstruction, HEDA1

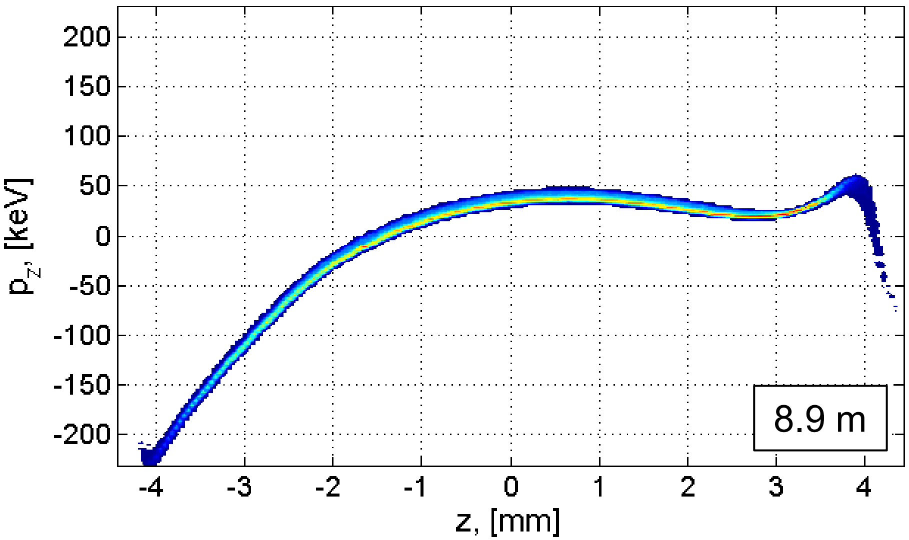




ART reconstruction, HEDA1

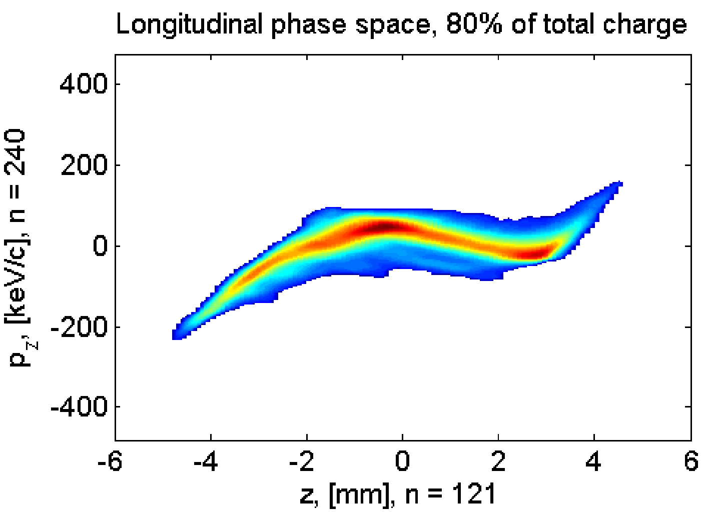


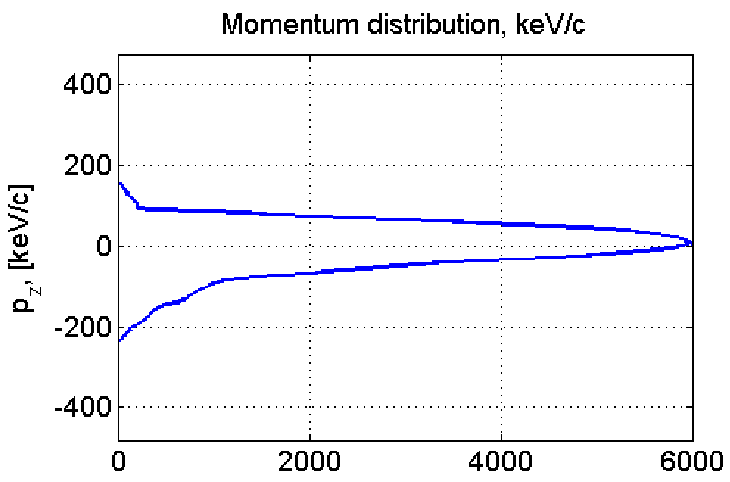
Reconstructed longitudinal phase space 100 iterations

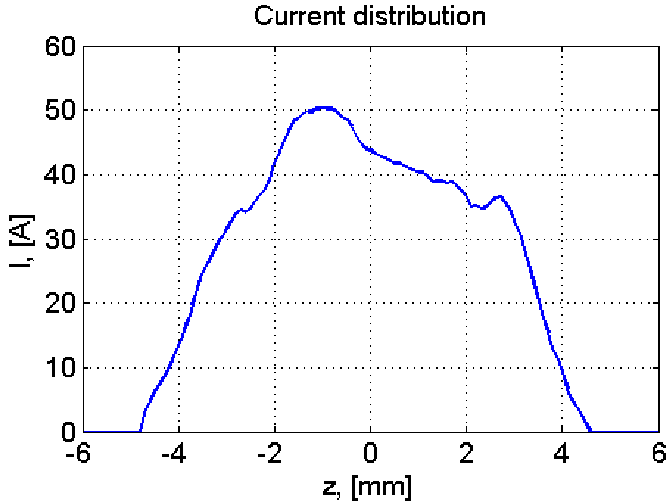


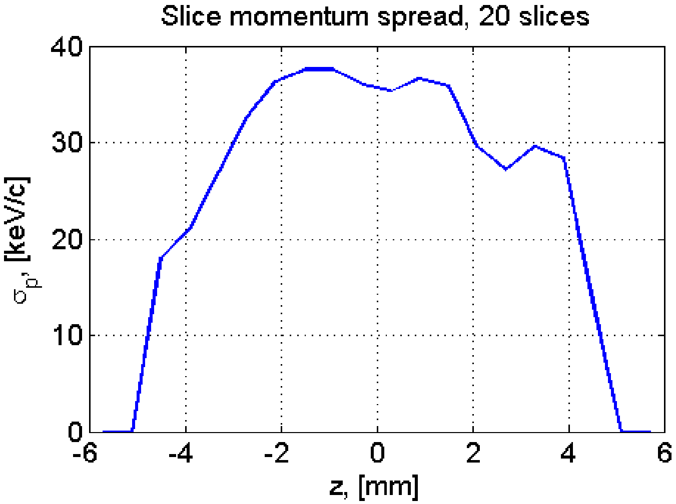
ASTRA longitudinal phase space

HEDA1, 1 nC bunch charge, 80% of charge

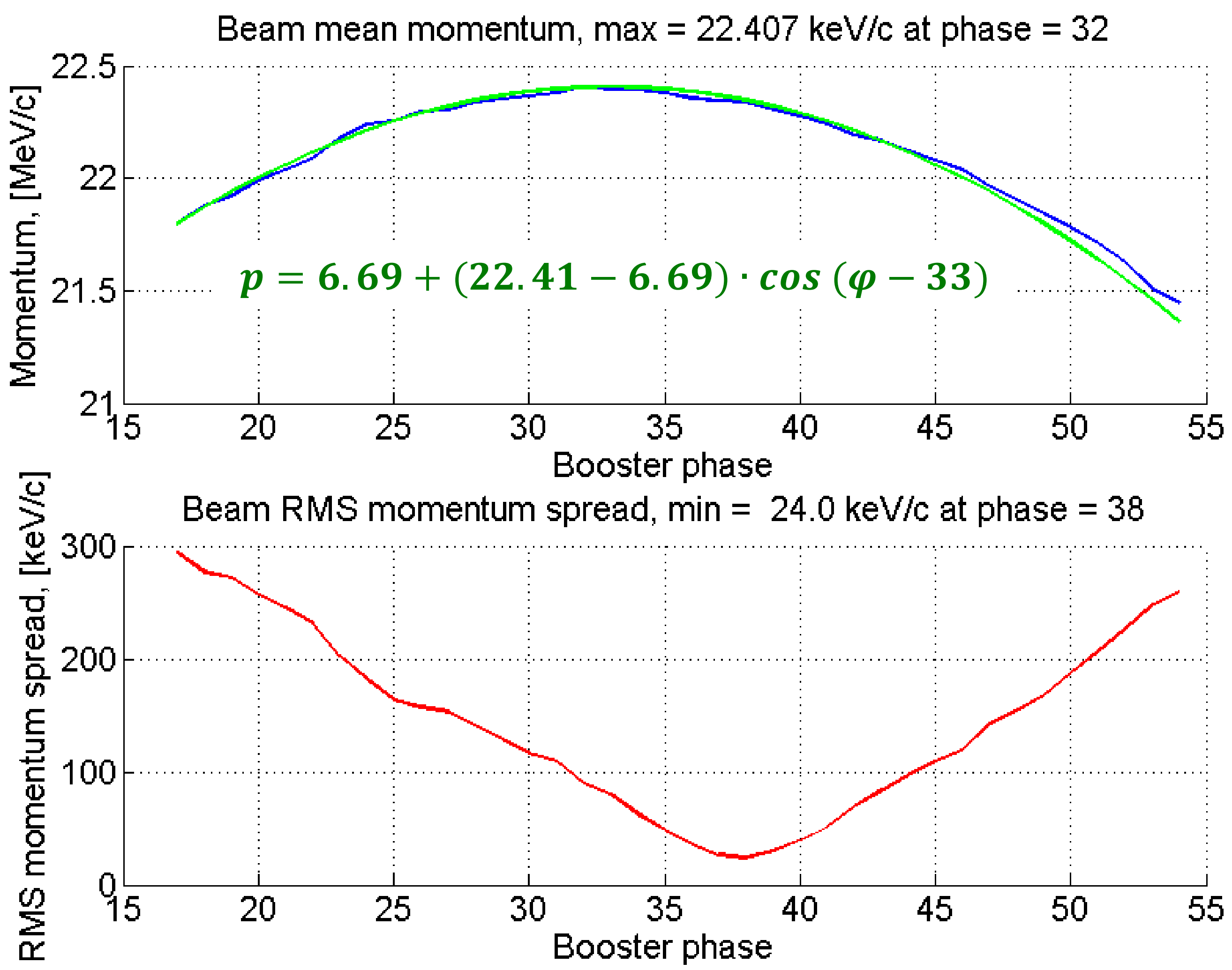




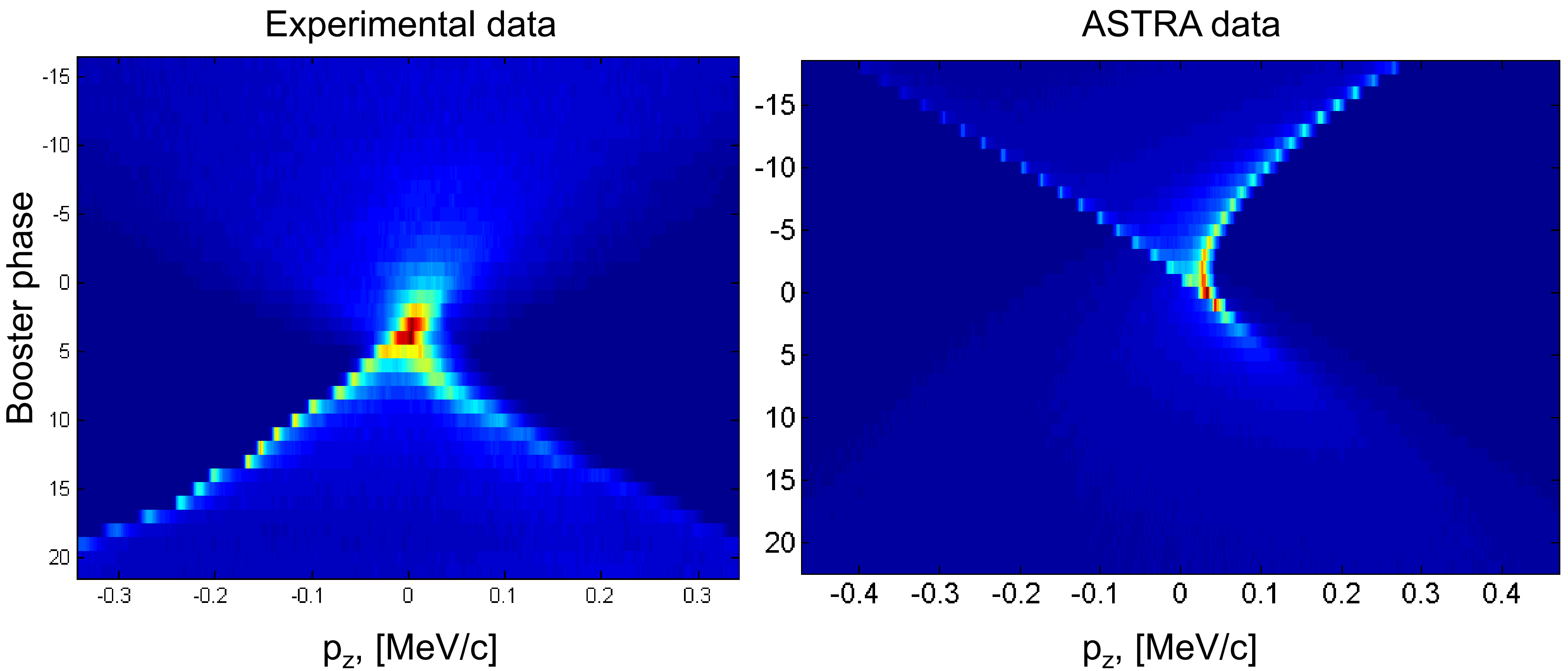




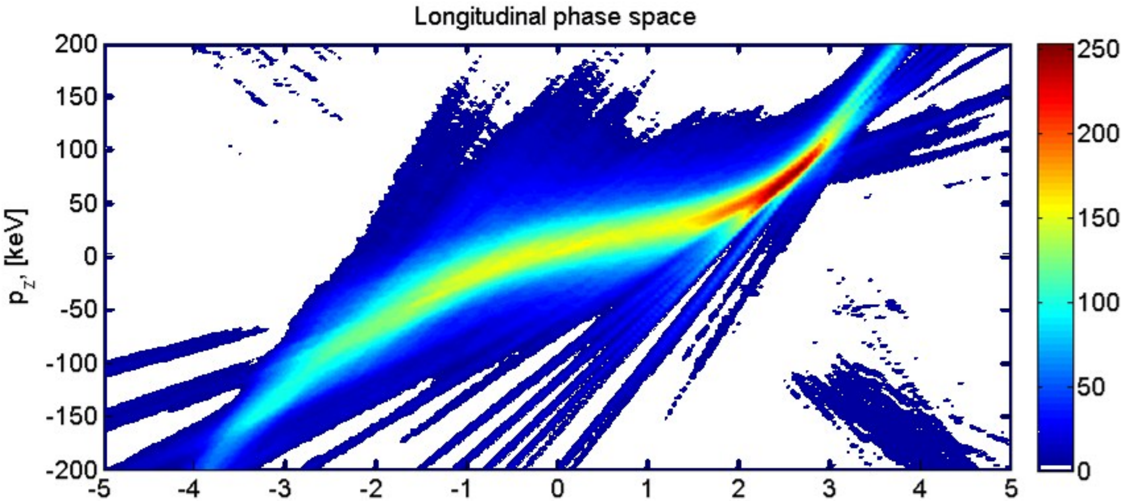
Data from 14.02.2013 20:50:46, HEDA2 momentum scan



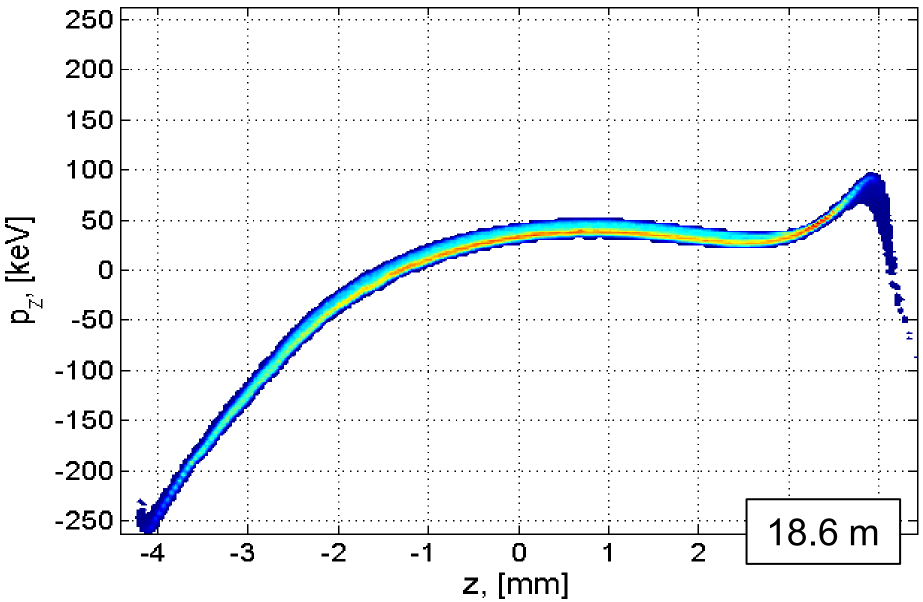
Initial data for reconstruction, HEDA2



ART reconstruction, HEDA2

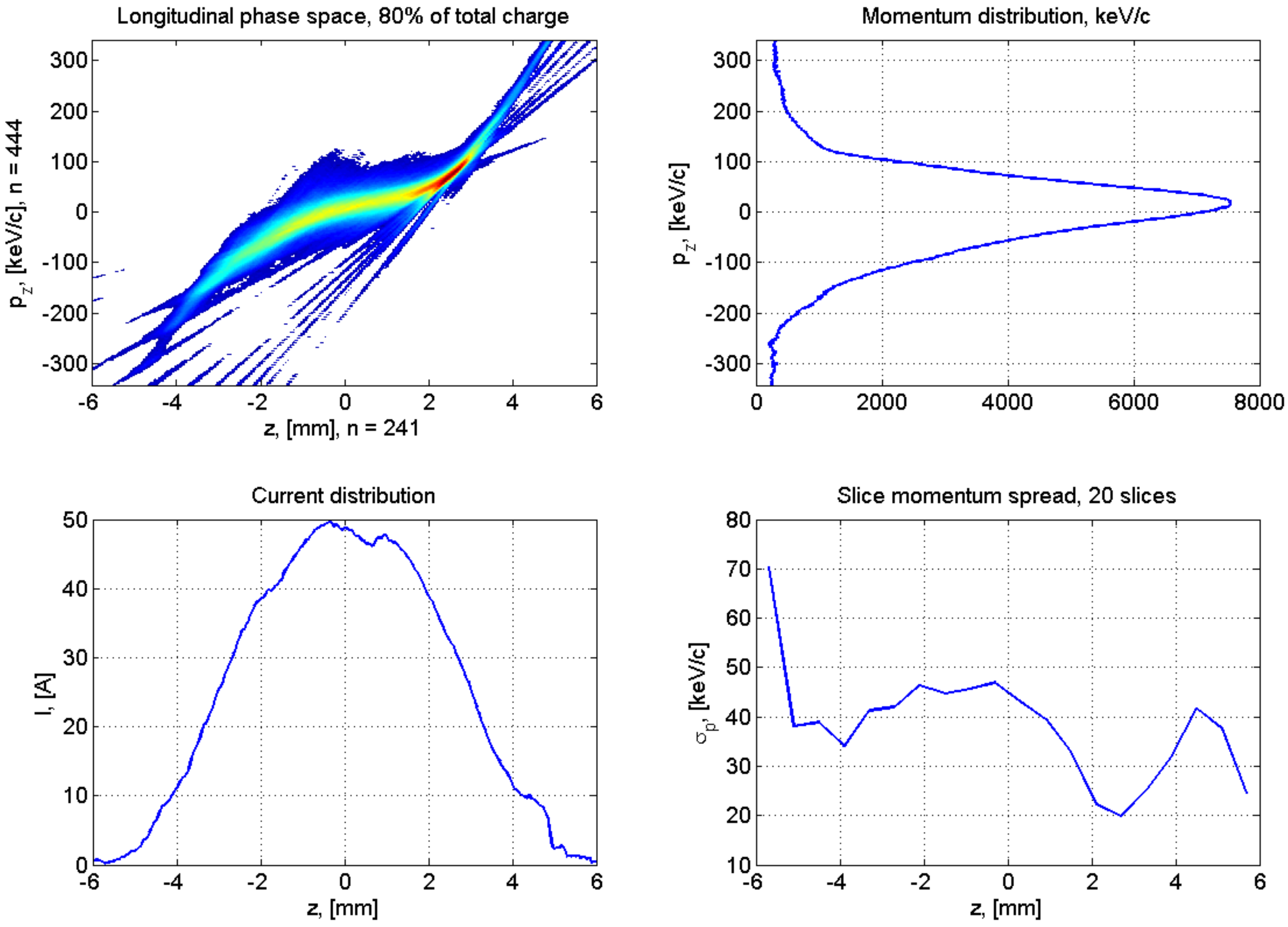


Reconstructed
longitudinal
phase
space
100 iterations



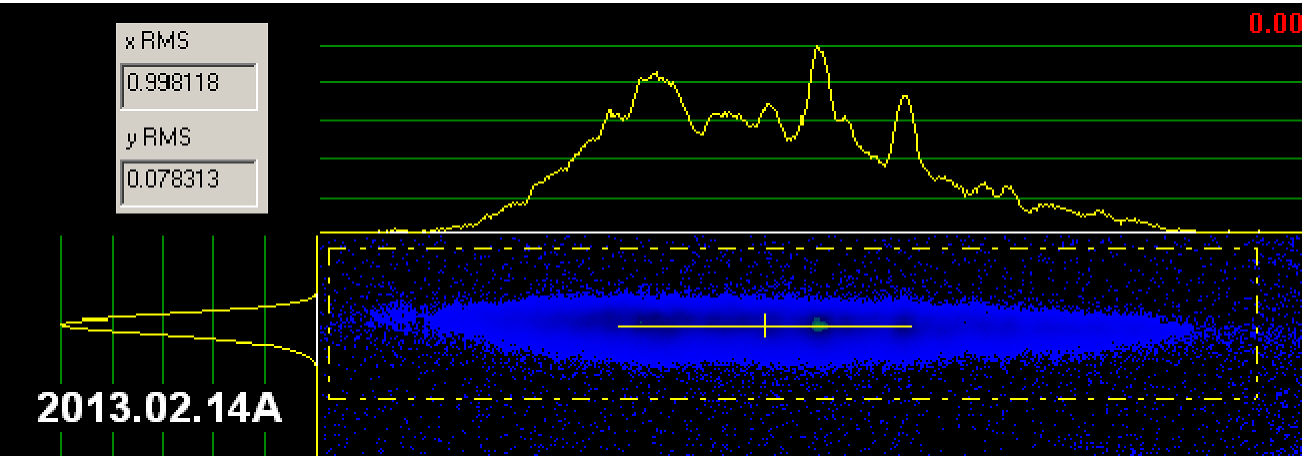
ASTRA
longitudinal phase space

HEDA2, 1 nC bunch charge, 80% of charge



Experimental data, machine parameters, setup II and III

100 pC HEDA1 reference screen



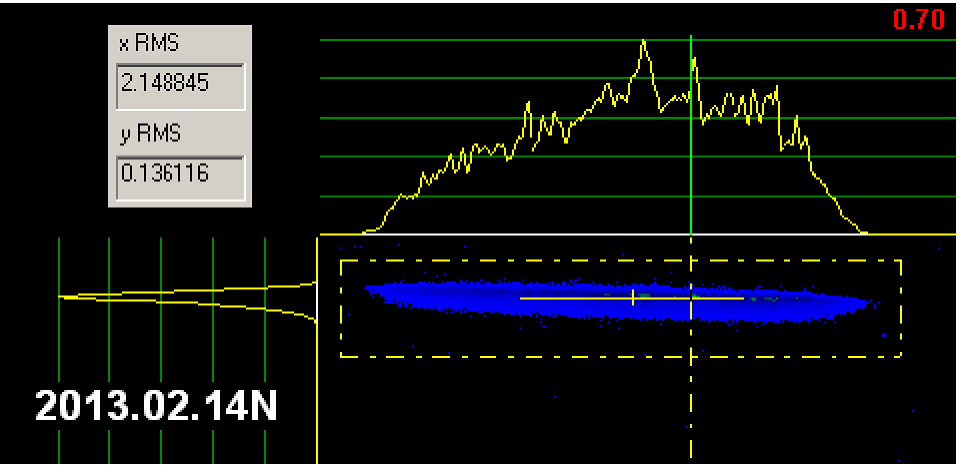
Momentum resolution:

$$\sigma_\delta = \frac{0.078 \cdot 10^{-3}}{0.6} = 0.13 \cdot 10^{-3}$$

For 22.2 MeV/c beam

→ 3 keV/c

20 pC HEDA1 reference screen



Momentum resolution:

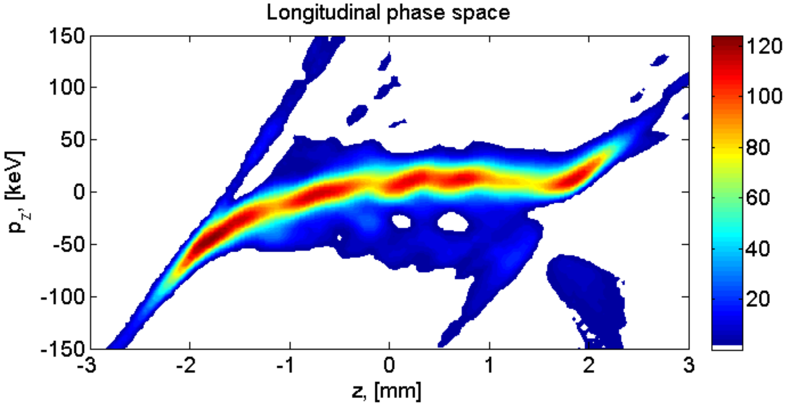
$$\sigma_\delta = \frac{0.136 \cdot 10^{-3}}{0.6} = 0.23 \cdot 10^{-3}$$

For 22.2 MeV/c beam

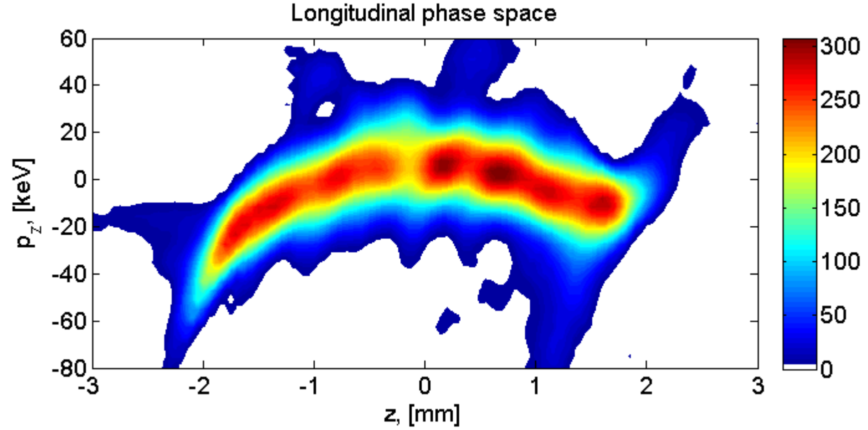
→ 5 keV/c

Reconstructed phase spaces 100 and 20 pC

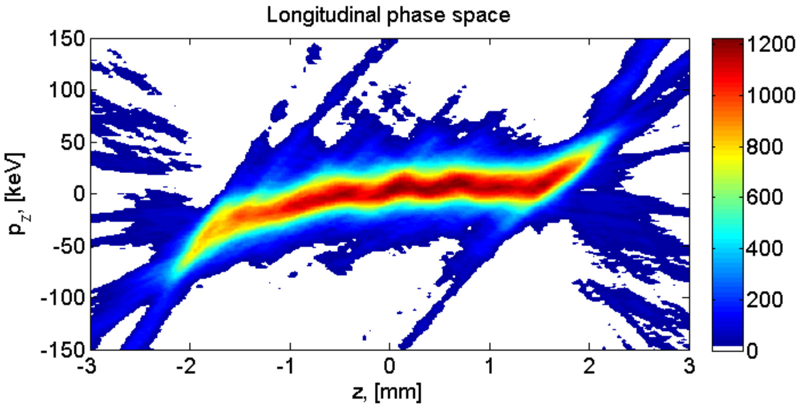
HEDA1 100 pC



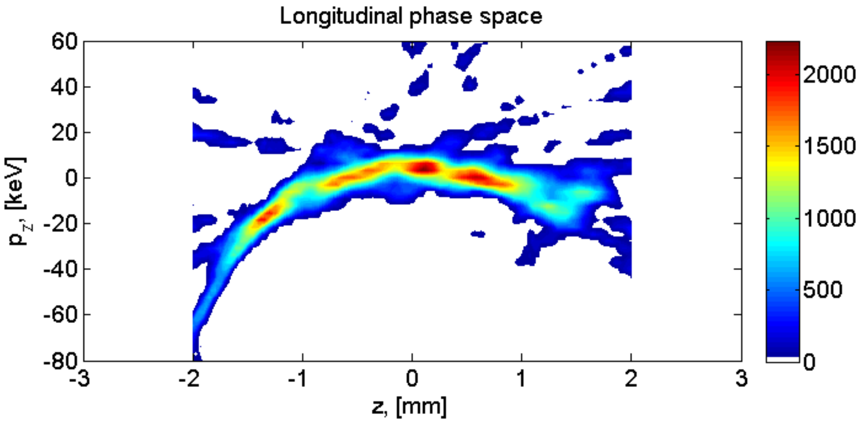
HEDA1 20 pC



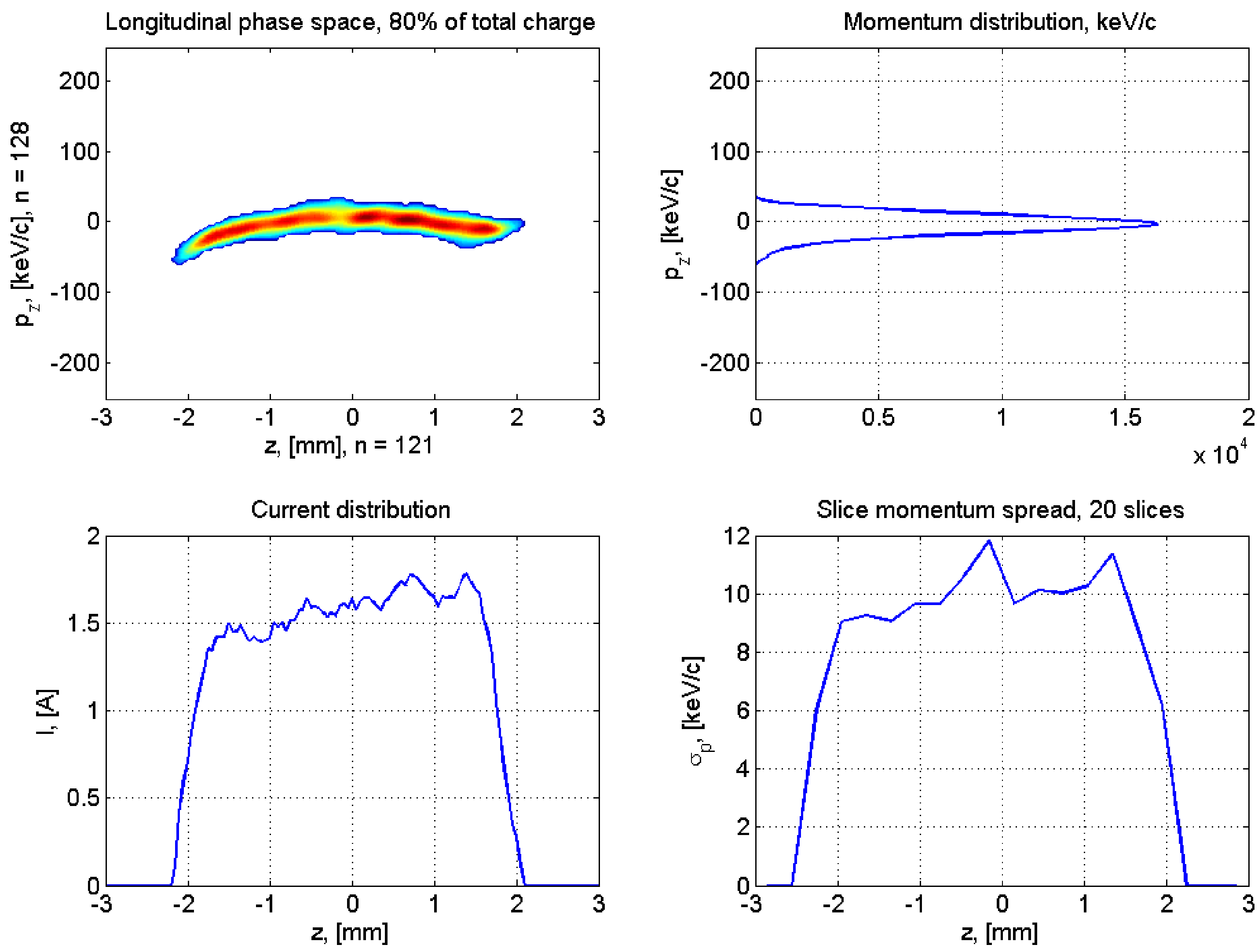
HEDA2 100 pC



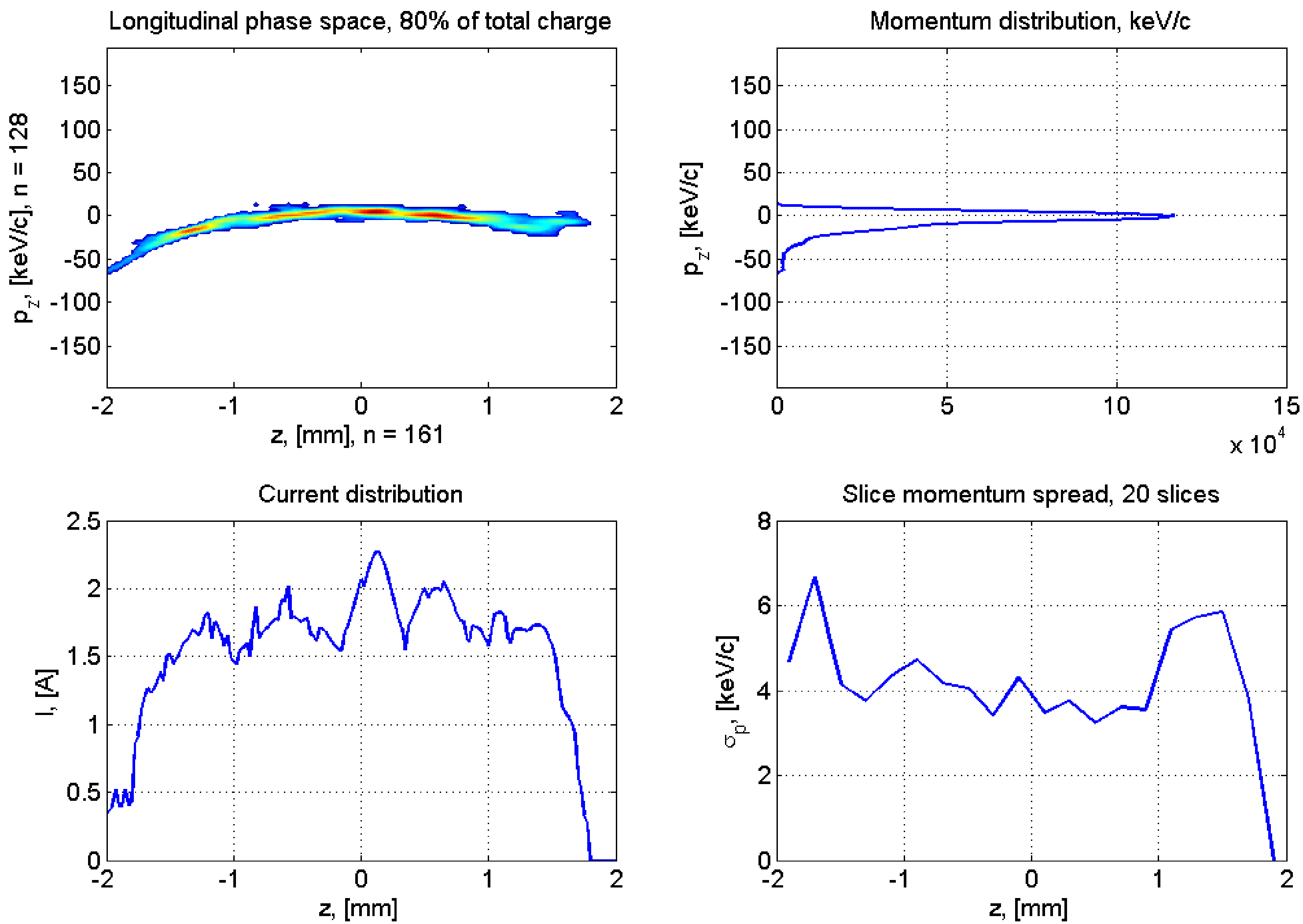
HEDA2 20 pC



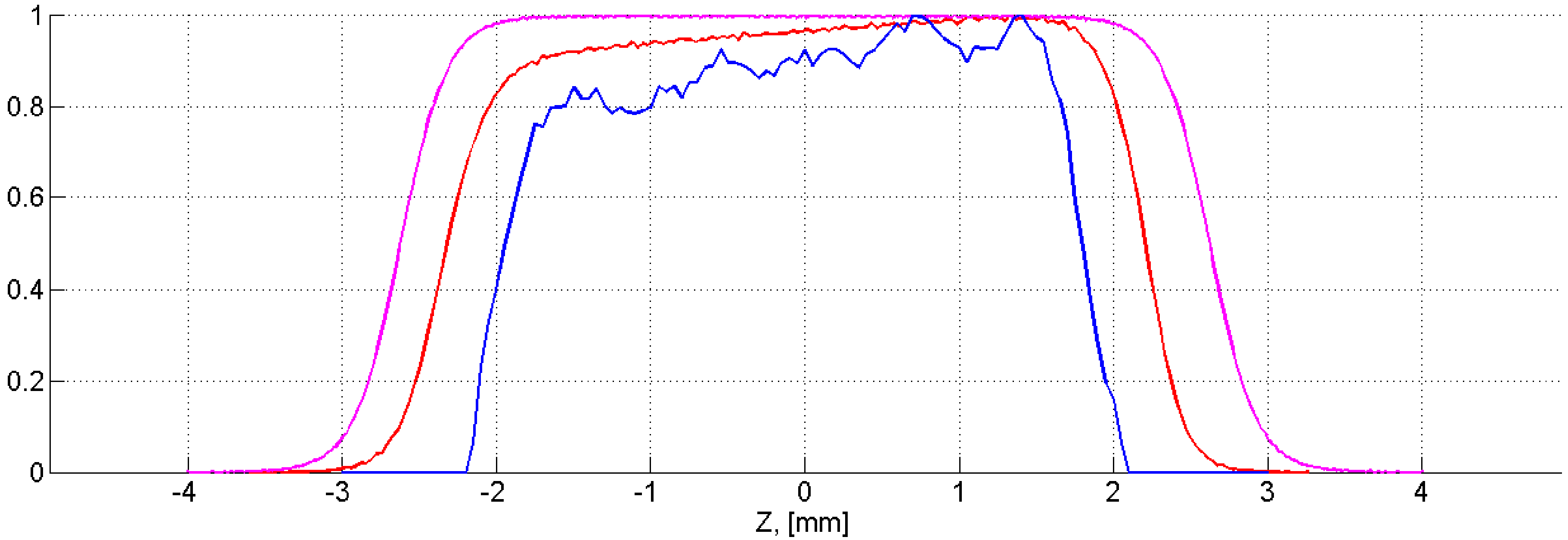
HEDA1 20 pC bunch charge



HEDA2 20 pC bunch charge

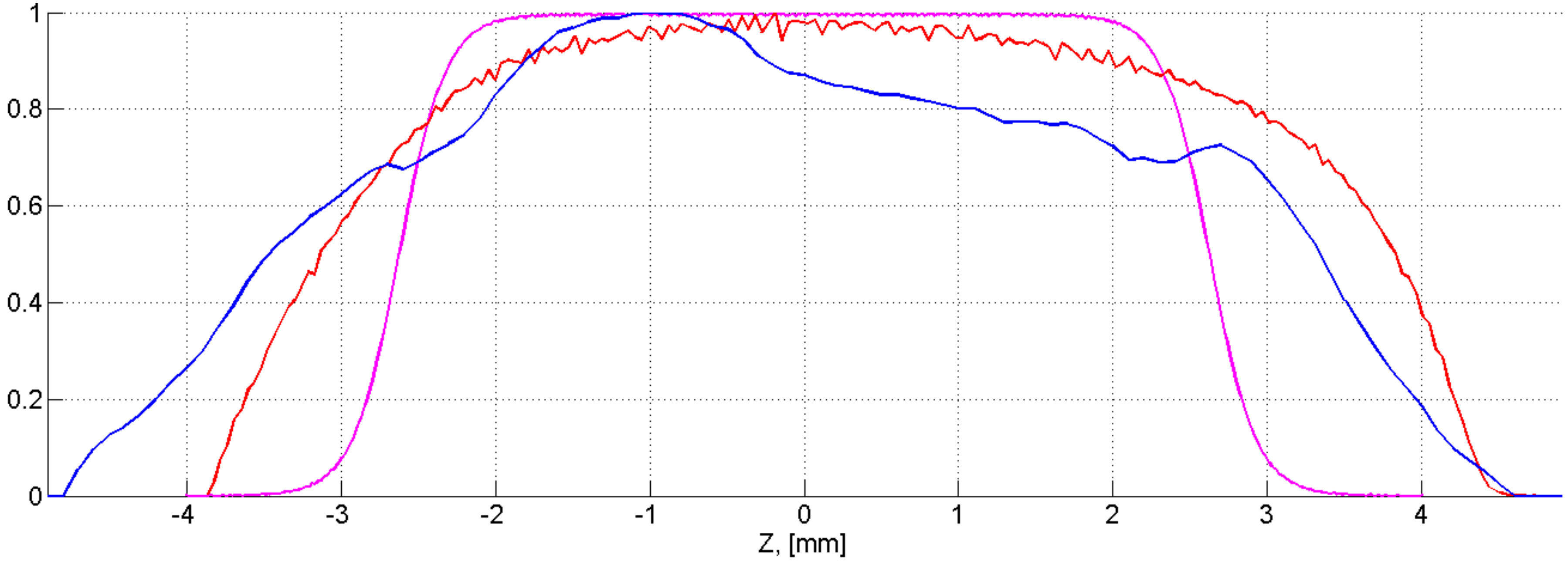


Longitudinal profiles at 8.92 for 20 pC bunch charge



Magenta line – laser profile (17.5 ps FWHM)
Red line – simulated bunch profile for 20 pC
Blue line – measured bunch profile for 20 pC

Longitudinal profiles at 8.92 for 1 nC bunch charge



Magenta line – laser profile (17.5 ps FWHM)
Red line – simulated bunch profile for 1 nC
Blue line – measured bunch profile for 1 nC

1. Overview of the PITZ facility
2. High momentum measurements at PITZ
3. Idea of the tomography
4. Algebraic reconstruction technique (ART)
5. Simulation of measurements in ASTRA
6. Experimental data, reconstruction results
7. **Conclusion**

Conclusion

- Simulation of the measurements in ASTRA gives results very close to the expected ones. This prove the idea of the longitudinal phase space measurements with the described tomography technique.
- The measured electron bunch longitudinal profiles show the similar shapes to the cathode laser temporal profiles. This demonstrates that the photo cathode has the short response time, less than ps.
- The measured electron bunch length for the 20 pC charge is shorter than the cathode laser pulse, what also can be seen in the ASTRA simulation.
- The measured electron bunch length for the 1 nC charge as well as simulated one is longer than the cathode laser pulse.