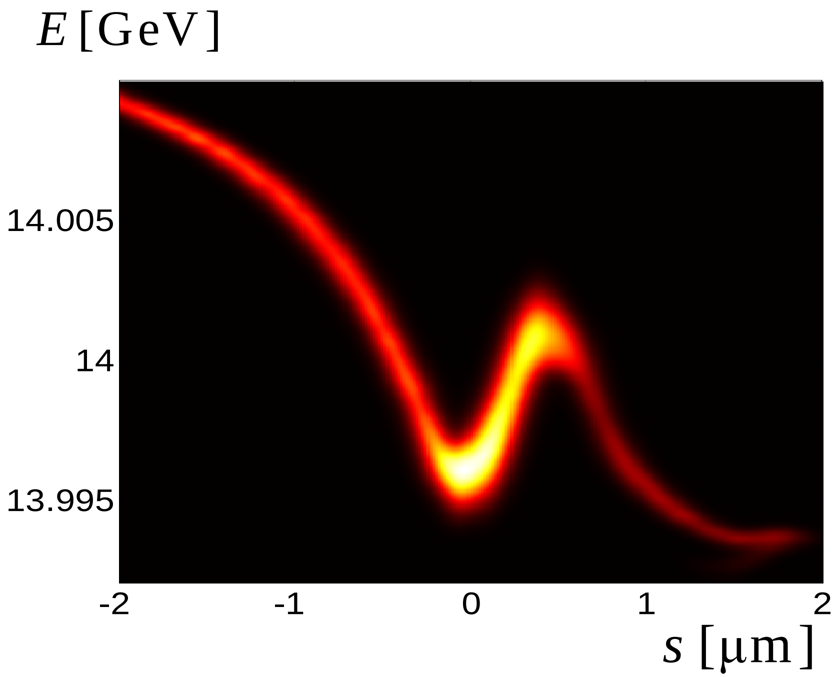
Charge and Bunch Length Scope

Compression Scenarios for the European XFEL



Igor Zagorodnov

1st Meeting of the European XFEL Accelerator Consortium

DESY, MPY

14. April 2012

HELMHOLTZ GEMEINSCHAFT

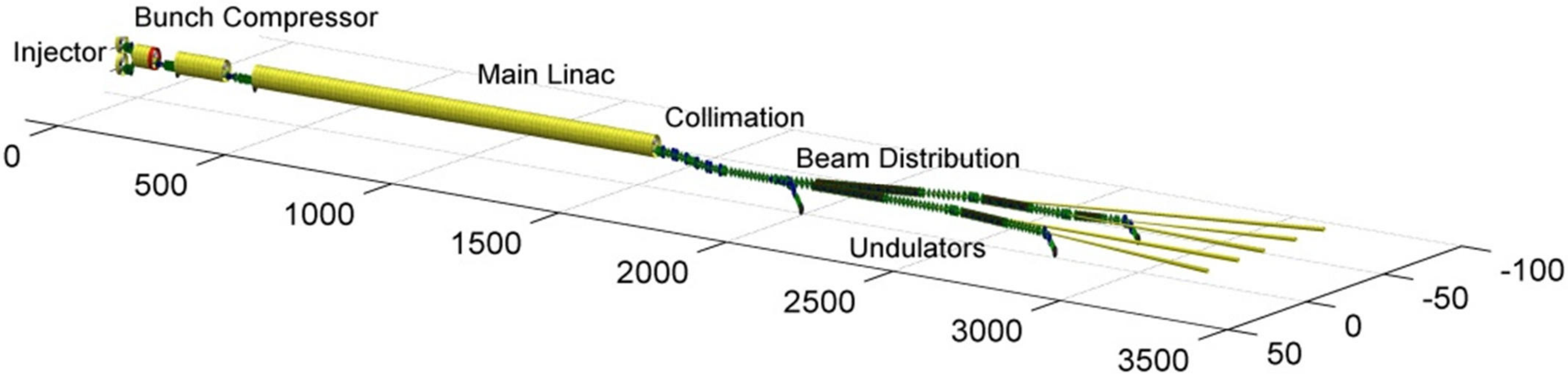
DESY

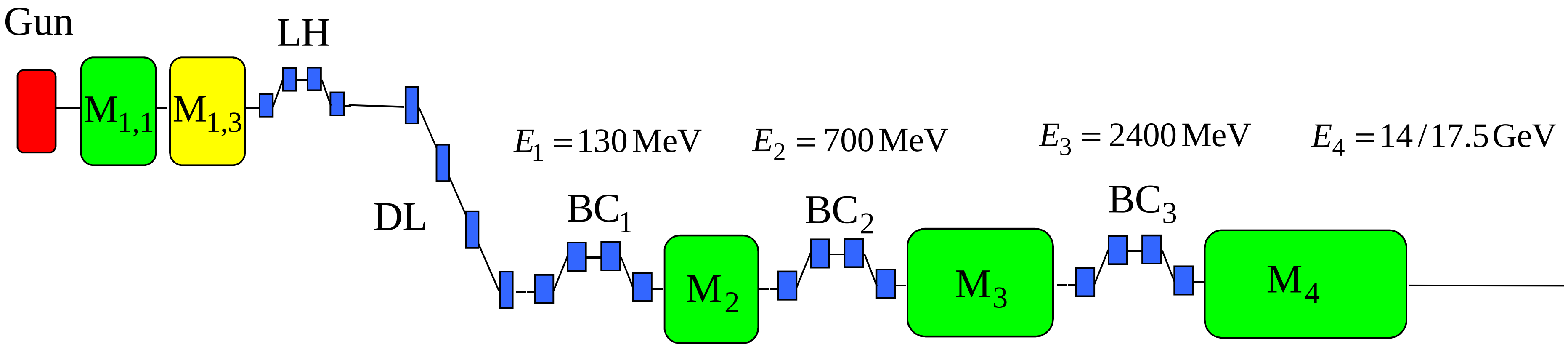
Inhalt

- Analytical and Numerical Approaches
- Compression Scenarios for Different Charges
- Strong Compression
- Summary

Analytical and Numerical Approaches

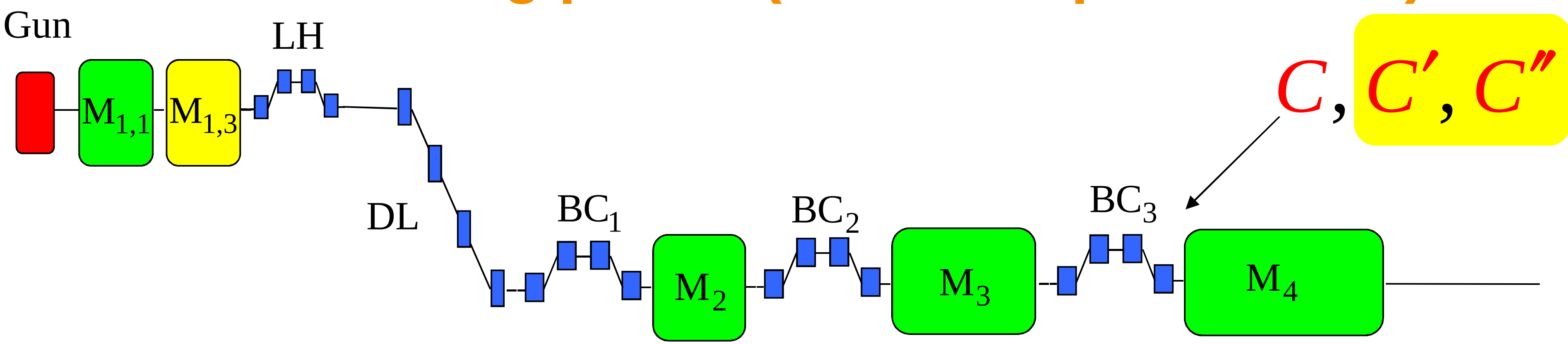
Layout





Analytical and Numerical Approaches

Working points (11 macro-parameters)



$E_1 = 130\,\mathrm{MeV}$ $\quad$ $E_2 = 700\,\mathrm{MeV}$ $\quad$ $E_3 = 2400\,\mathrm{MeV}$

$R_{56,1} = ?$ $\quad$ $R_{56,2} = ?$ $\quad$ $R_{56,3} = ?$

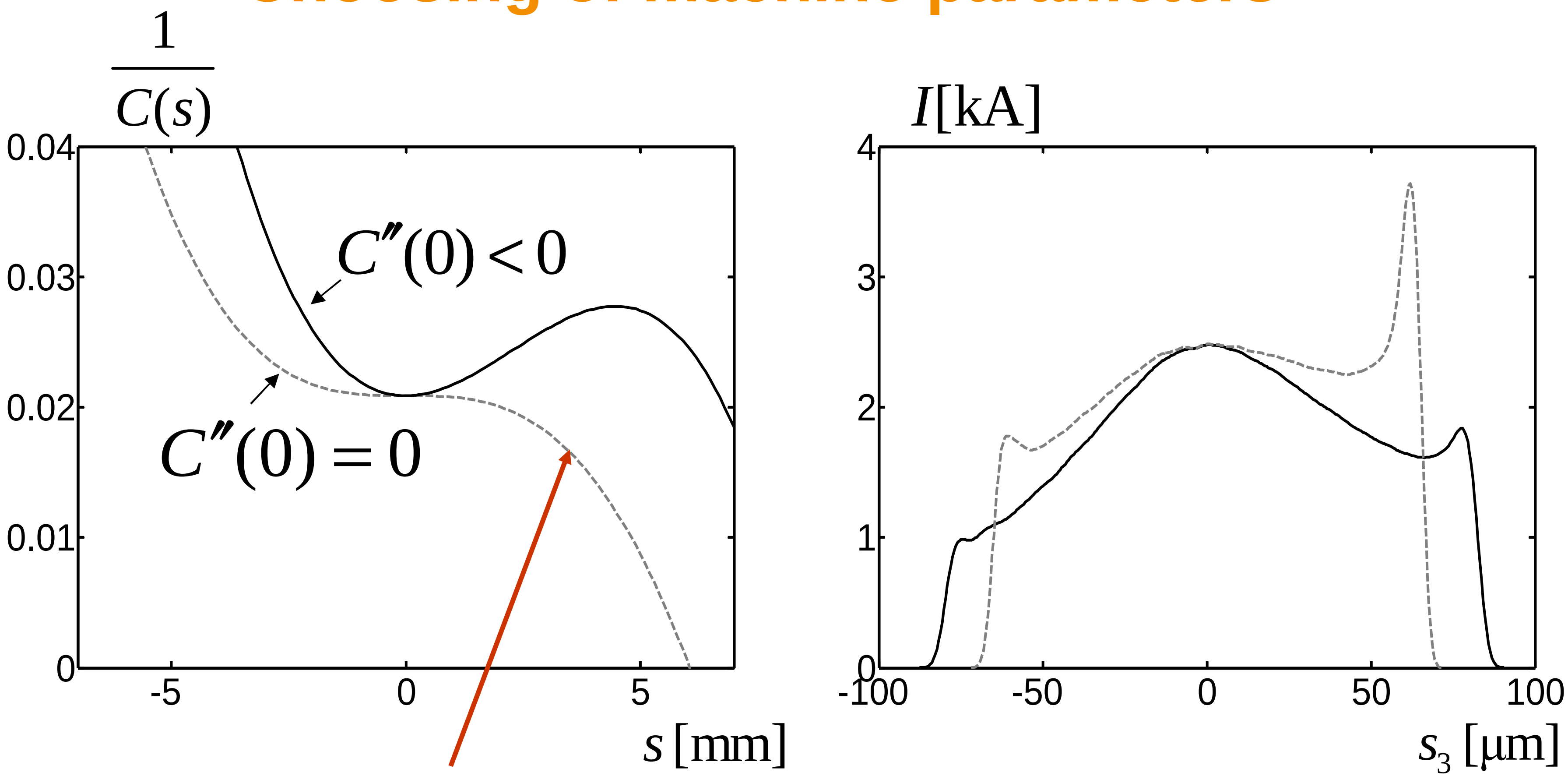
$C_1 = ?$ $\quad$ $C_2 = ?$

What is the optimal choice?

Zagorodnov I., Dohlus M., *A Semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects*, Phys. Rev. ST Accel. Beams, 2011.

Analytical and Numerical Approaches

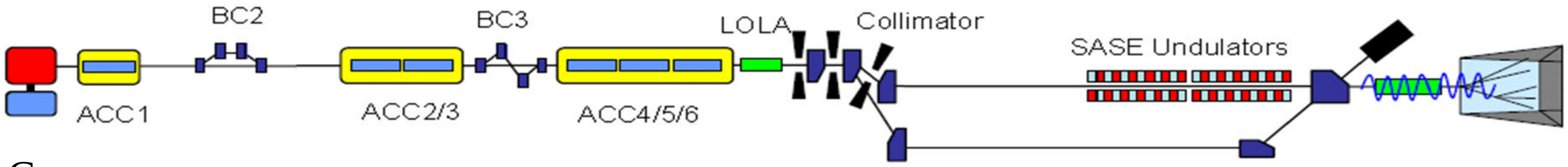
Choosing of machine parameters



very strong compression
at the bunch head (spike)

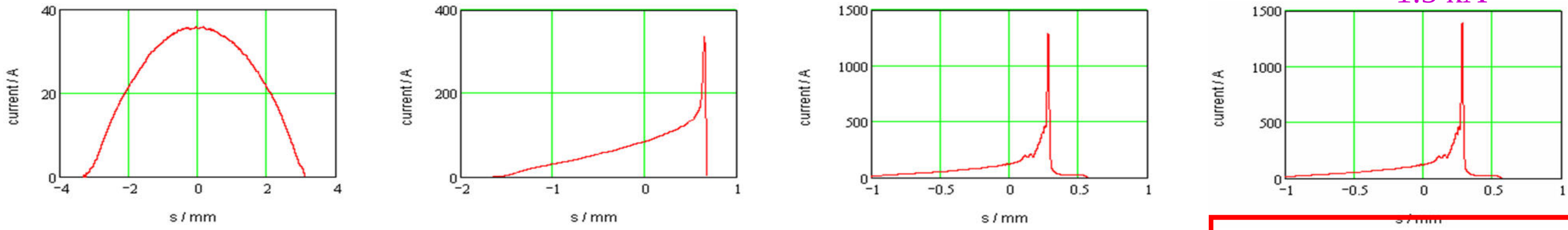
Analytical and Numerical Approaches

Rollover Compression vs. Linearized (FLASH)

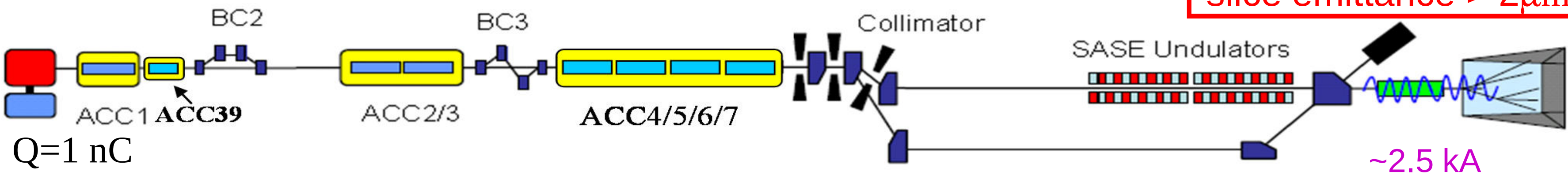


Q=0.5 nC

~ 1.5 kA

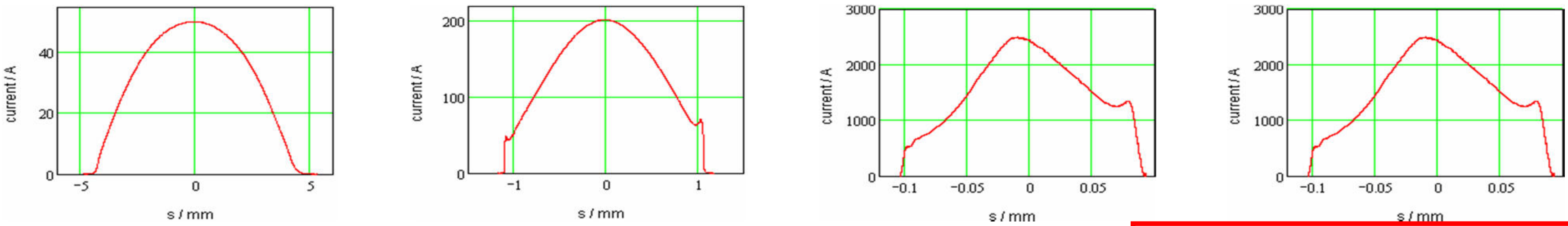


slice emittance > 2μm



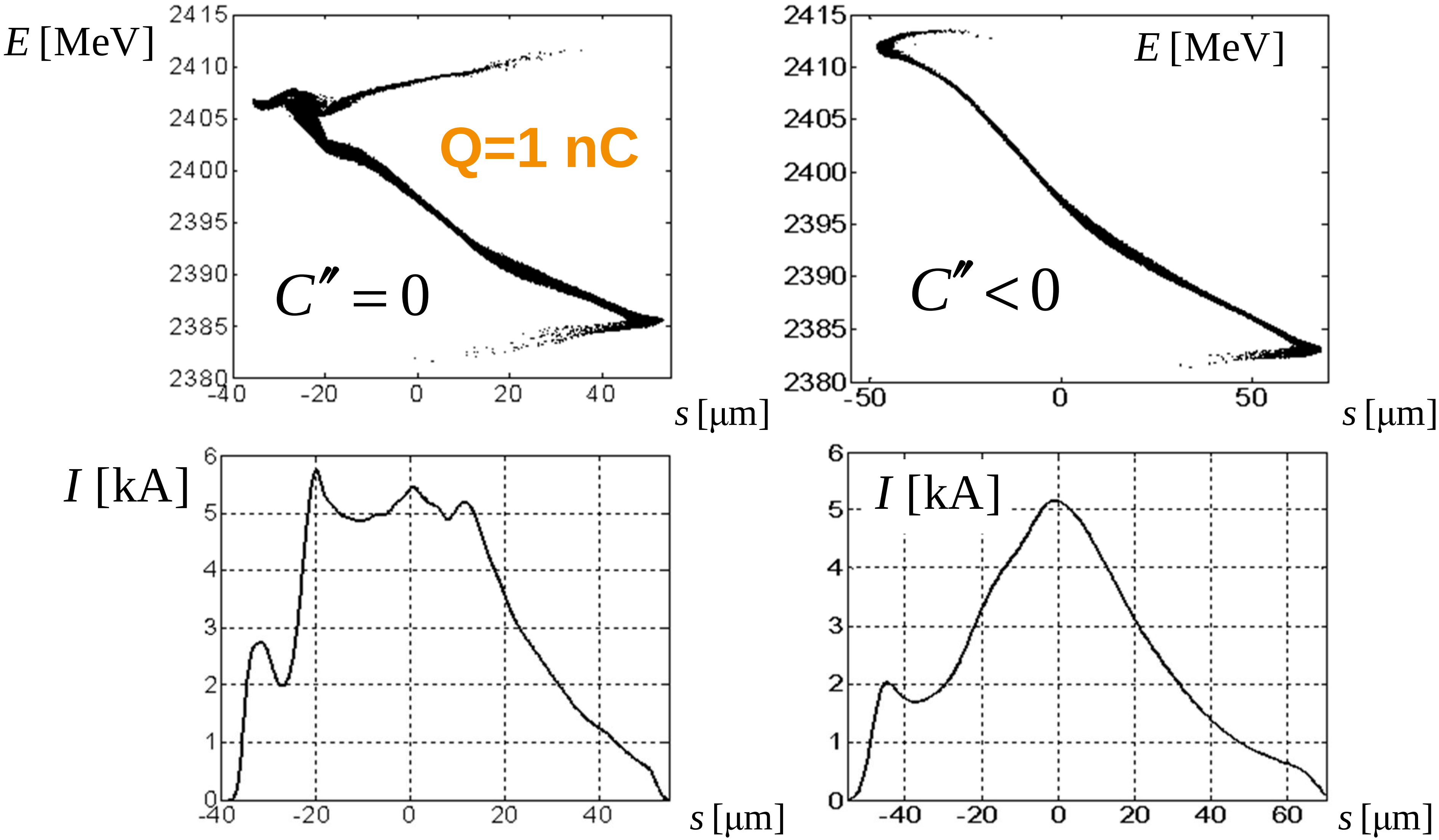
Q=1 nC

~2.5 kA



slice emittance ~ 0.3 - 1μm

Analytical and Numerical Approaches



Analytical and Numerical Approaches

Analytical solution without self-fields

$$\mathbf{x}_0 = \mathbf{A}_0^{-1}(\mathbf{f}_0)$$

Solution with self-fields

$$\mathbf{A}(\mathbf{x}) = \mathbf{f}_0$$

nonlinear operator (tracking with self-fields)

$$\mathbf{x} = \mathbf{A}_0^{-1}\left(\mathbf{A}_0(\mathbf{x}) + \mathbf{f}_0 - \mathbf{A}(\mathbf{x})\right)$$

$$\mathbf{x}_n = \mathbf{A}_0^{-1}\left(\mathbf{A}_0(\mathbf{x}_{n-1}) + \mathbf{f}_0 - \mathbf{A}(\mathbf{x}_{n-1})\right)$$

$$\mathbf{f}_0 = \begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ C_1 \\ C_2 \\ C \\ C' \\ C'' \end{pmatrix} \Rightarrow \mathbf{x} = \begin{pmatrix} V_{1,1} \\ \varphi_{1,1} \\ V_{1,3} \\ \varphi_{1,3} \\ V_2 \\ \varphi_2 \\ V_3 \\ \varphi_3 \end{pmatrix}$$

numerical tracking

$$\mathbf{f}_{n-1} = \mathbf{A}(\mathbf{x}_{n-1})$$
$$\Delta\mathbf{f}_{n-1} = \mathbf{f}_0 - \mathbf{f}_{n-1}$$
$$\mathbf{g}_n = \mathbf{g}_{n-1} + \Delta\mathbf{f}_{n-1}$$
$$\mathbf{x}_n = \mathbf{A}_0^{-1}(\mathbf{g}_n)$$

residual in macroscopic parameters

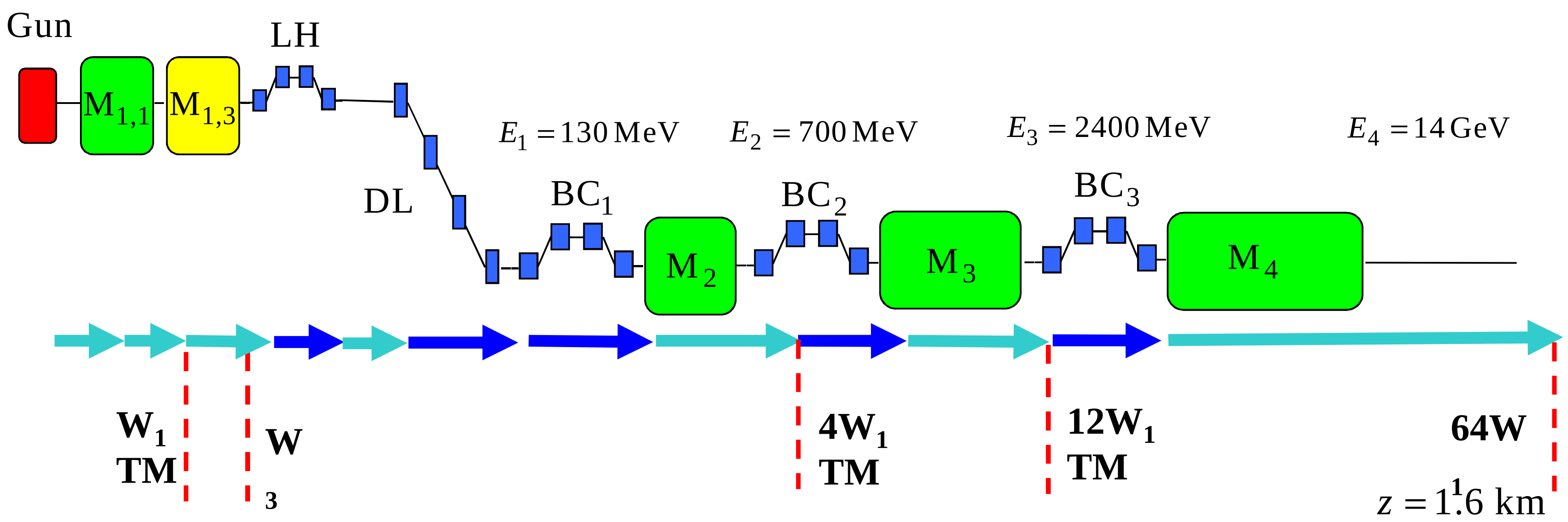
analytical correction of RF parameters

Zagorodnov I., Dohlus M., *A Semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects*, Phys. Rev. ST Accel. Beams, 2011.

Analytical and Numerical Approaches

Beam dynamics simulation

Full 3D simulation method (**200 CPU, ~10 hours**)



ASTRA (tracking with **3D space charge**, DESY, K. Flötmann)

CSRtrack (tracking through dipoles, DESY, M. Dohlus, T. Limberg)

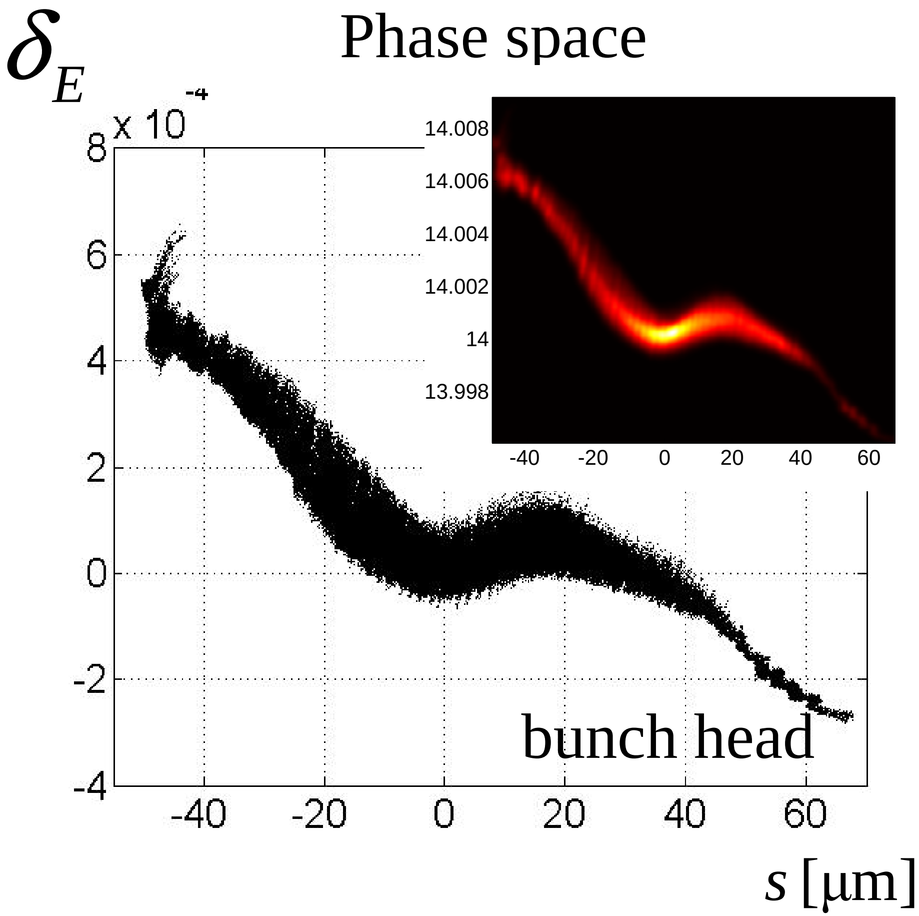
W1 -TESLA cryomodule wake (TESLA Report 2003-19, DESY, 2003)

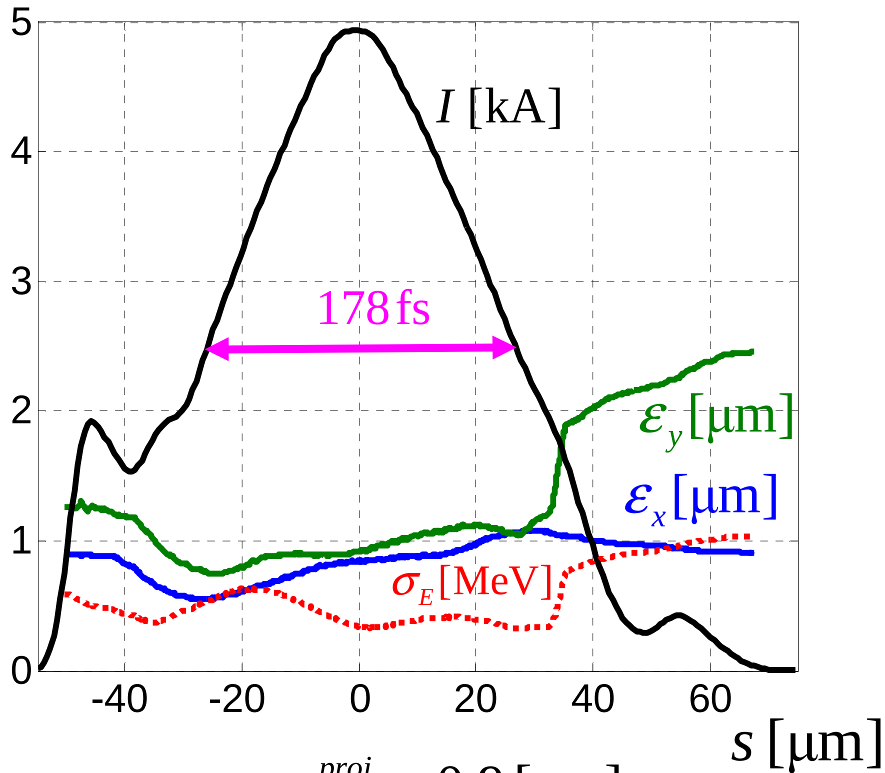
W3 - ACC39 wake (TESLA Report 2004-01, DESY, 2004)

TM - transverse matching to the design optics

Compression for Different Charges

Q=1 nC



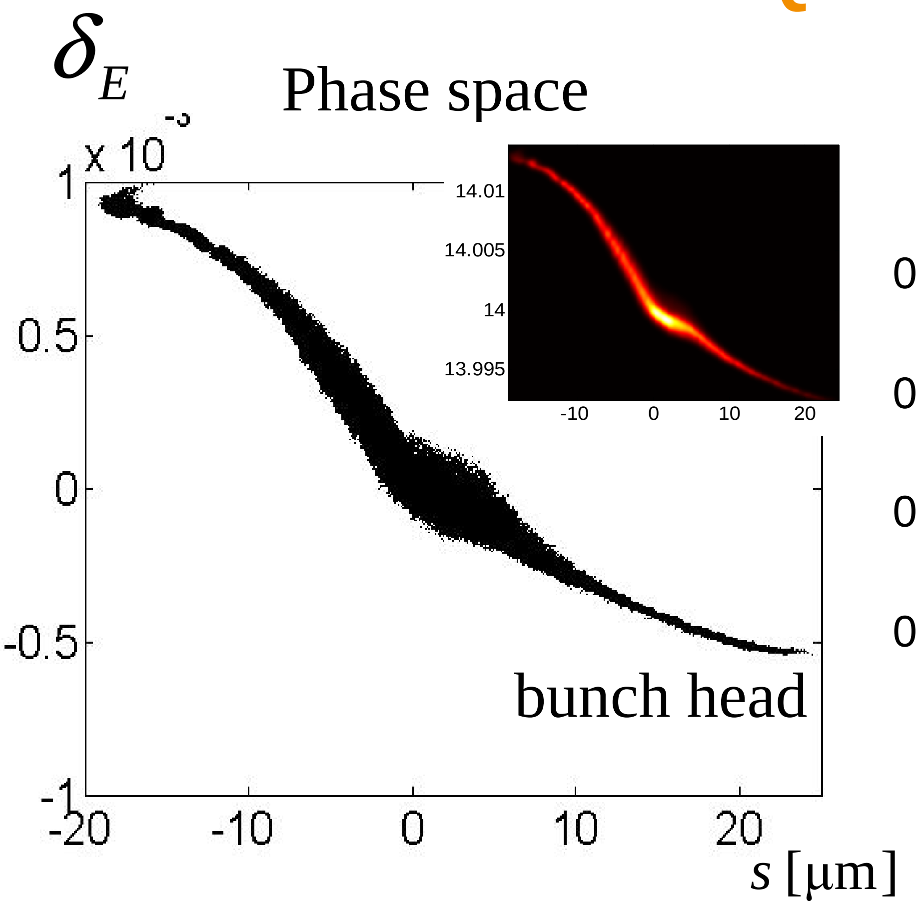


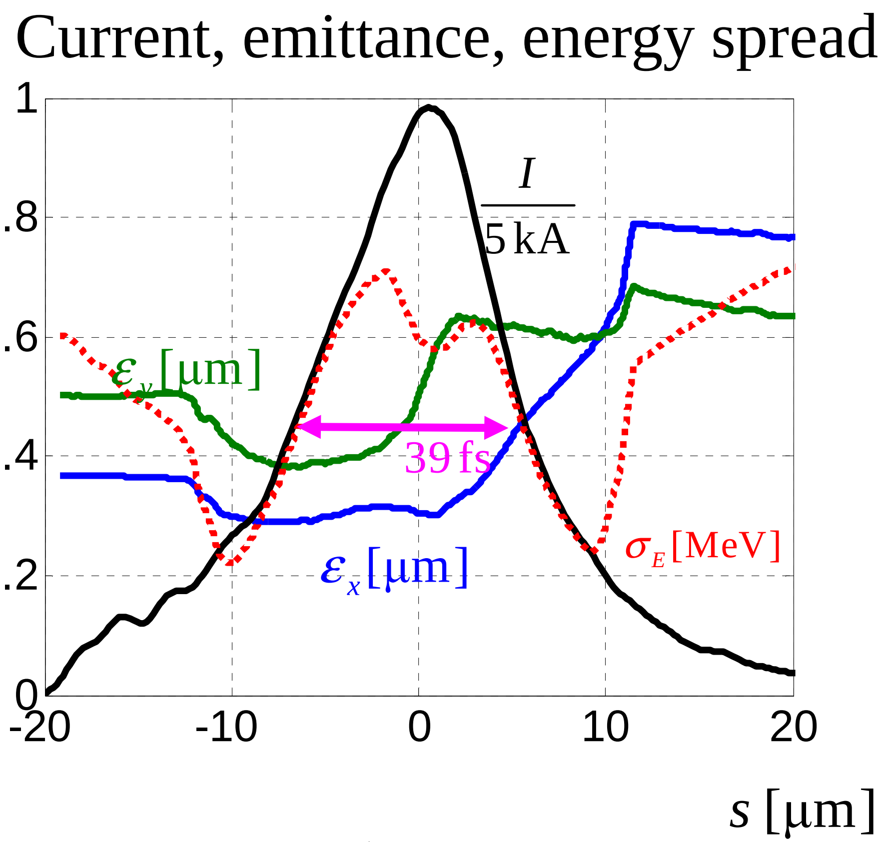
$$\varepsilon_x^{proj} = 0.9\,[\mu m]$$

$$\varepsilon_y^{proj} = 3.5\,[\mu m]$$

Compression for Different Charges

Q=250 pC



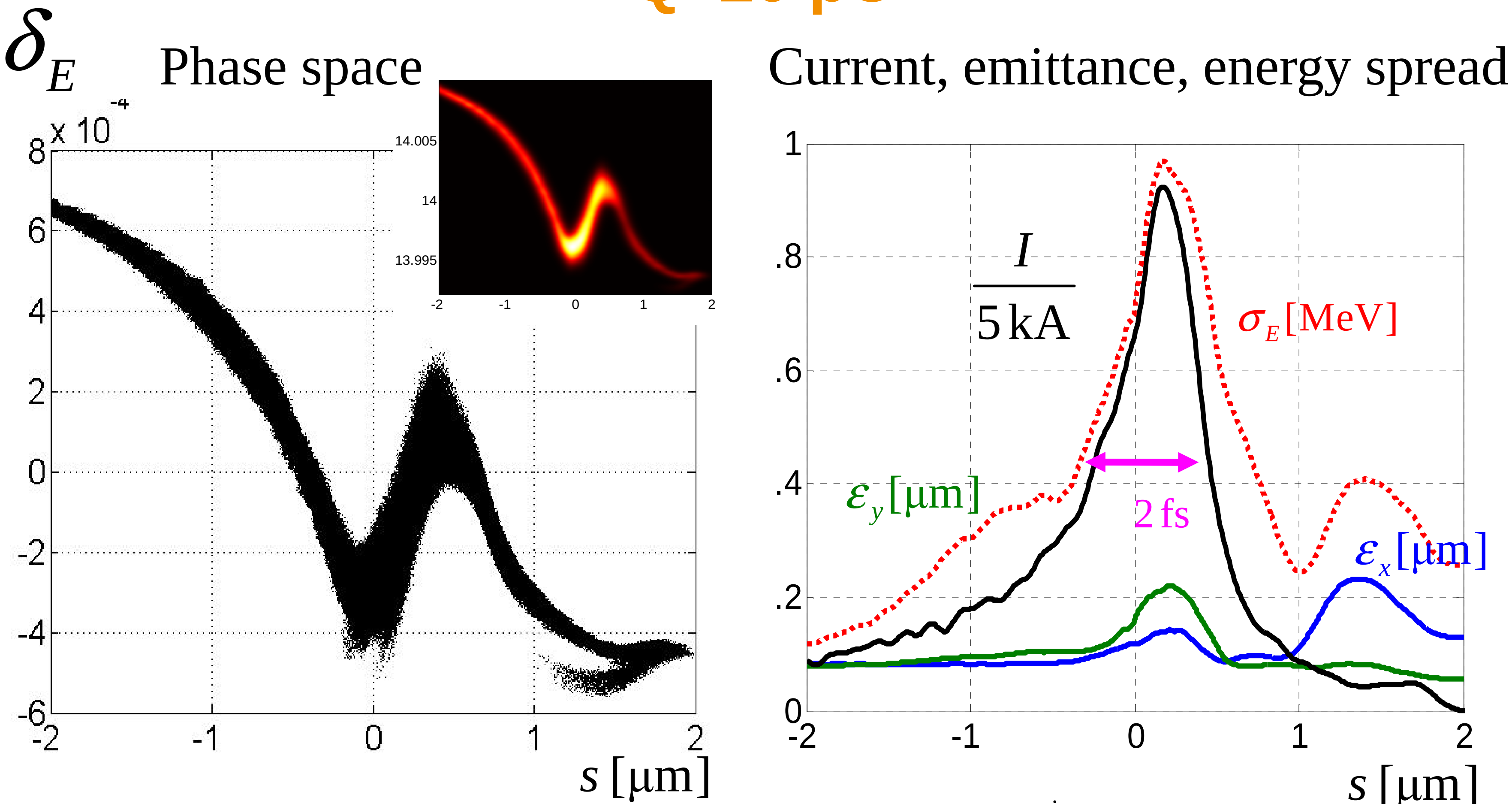


$$\varepsilon_x^{proj} = 0.45\,[\mu\mathrm{m}]$$

$$\varepsilon_y^{proj} = 1.5\,[\mu\mathrm{m}]$$

Compression for Different Charges

Q=20 pC



$$\varepsilon_x^{proj} = 0.14\,[\mu\text{m}]$$

$$\varepsilon_y^{proj} = 0.26\,[\mu\text{m}]$$

DESY

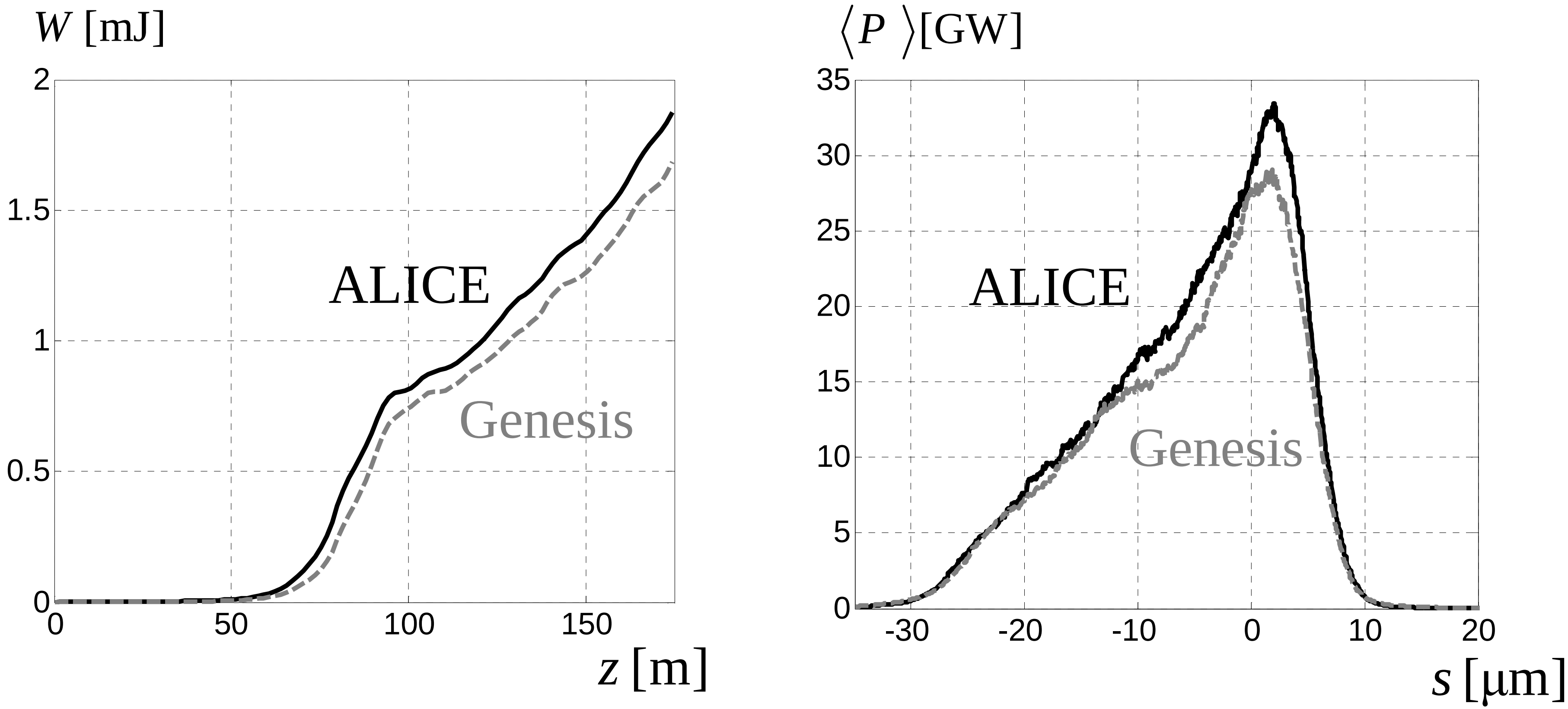
Compression for Different Charges

Beam parameters from S2E simulations

Parameter	Unit					
Bunch charge	nC	1	0.5	0.25	0.1	0.02
Peak current (gun)	A	43	24	13.5	5.7	1.2
Bunch length (gun, FWHM)	ps	25	22	20	17	17
Slice emittance (gun)	µm	0.8	0.5	0.3	0.21	0.09
Projected emittance (gun)	µm	1	0.7	0.6	0.3	0.1
Compression		114	233	363	877	3833
Peak current	kA	**4.9**	**5.6**	**4.9**	**5**	**4.6**
Bunch length (FWHM)	fs	178	72	39	12	2.2
Slice emittance	µm	**1**	**0.7**	**0.5**	**0.3**	**0.17**
Projected emittance	µm	3.5	2.2	1.5	0.84	0.26
Slice energy spread **(laser heater off)**	MeV	0.45	0.44	0.6	0.6	0.8

Compression for Different Charges

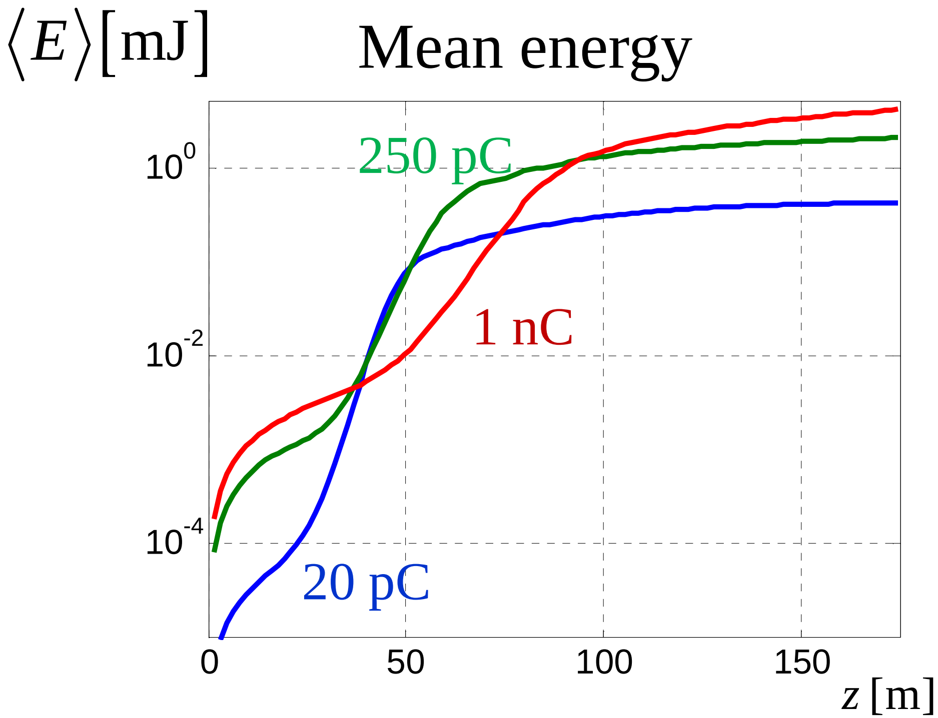
Radiation Q=1nC. SASE

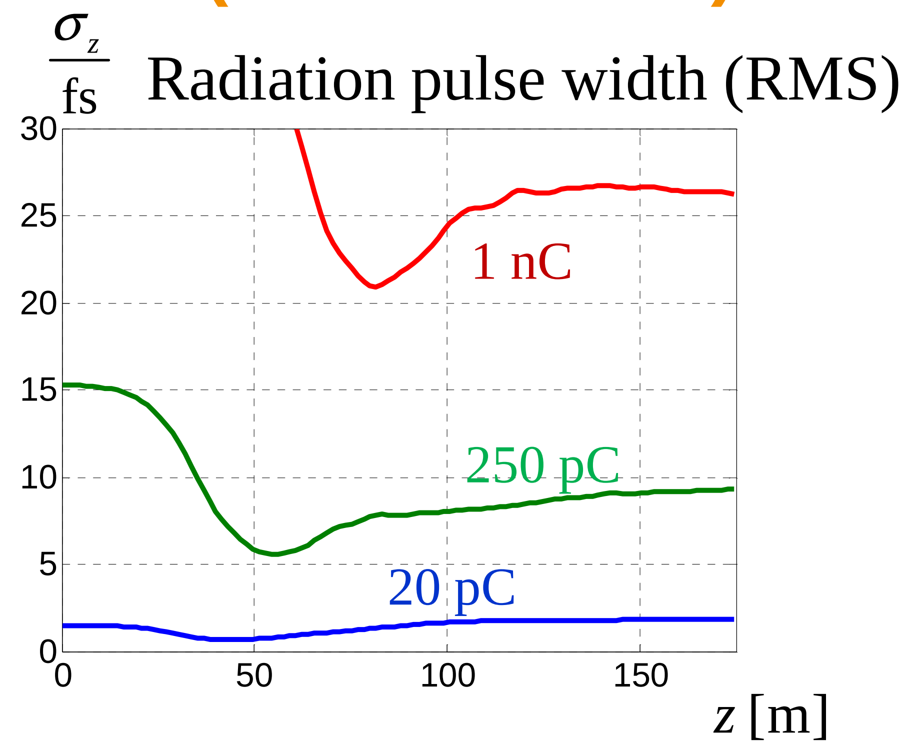


Zagorodnov I., Dohlus M., *Numerical FEL studies with a new code ALICE*, in Proceedings of FEL09, Liverpool, 2009.

Compression for Different Charges

Radiation energy statistics (1-25-120 runs)





Charge, nC	1	0.25	0.02
Mean radiation energy, mJ	1-4	1-2	0.1-0.4
Pulse radiation width (FWHM), fs	**25-50**	**10-20**	**1-2**

Compression for Different Charges

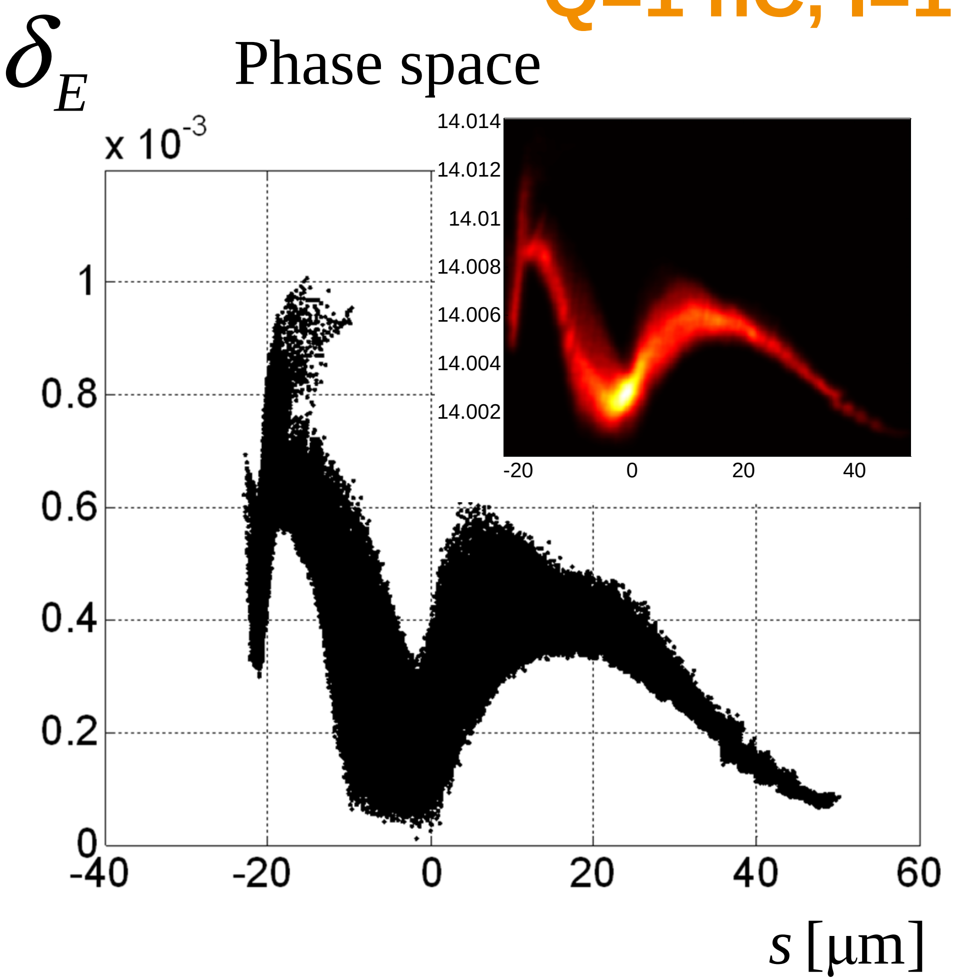
Radiation Properties from S2E

Bunch charge, nC	1	0.25	0.02
Wavelength, nm	0.1		
Beam energy, GeV	14		
Peak current, kA	**~ 5**		
Slice emmitance,mm-mrad	**1**	**0.5**	**0.2**
Saturation length, m	**85**	**60**	**45**
Energy in the rad. pulse, mJ	1-4	1-2	0.1-0.4
Radiation pulse duration FWHM, fs	**25-50**	**10-20**	**1-2**
Averaged peak power, GW	**10-50**	**10-100**	**50-150**
Spectrum width, %		0.15-0.3	0.18-0.5

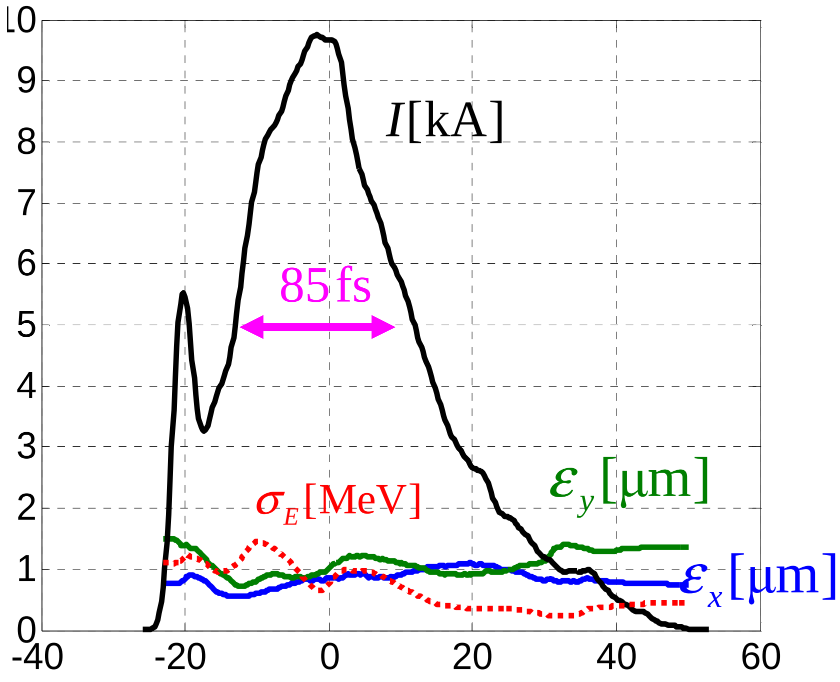
Strong Compression

Q=1 nC, I=10kA

Phase space



Current, emittance, energy spread



$$\varepsilon_x^{proj} = 0.9\,[\mu m]$$

$$\varepsilon_y^{proj} = 8\,[\mu m]$$

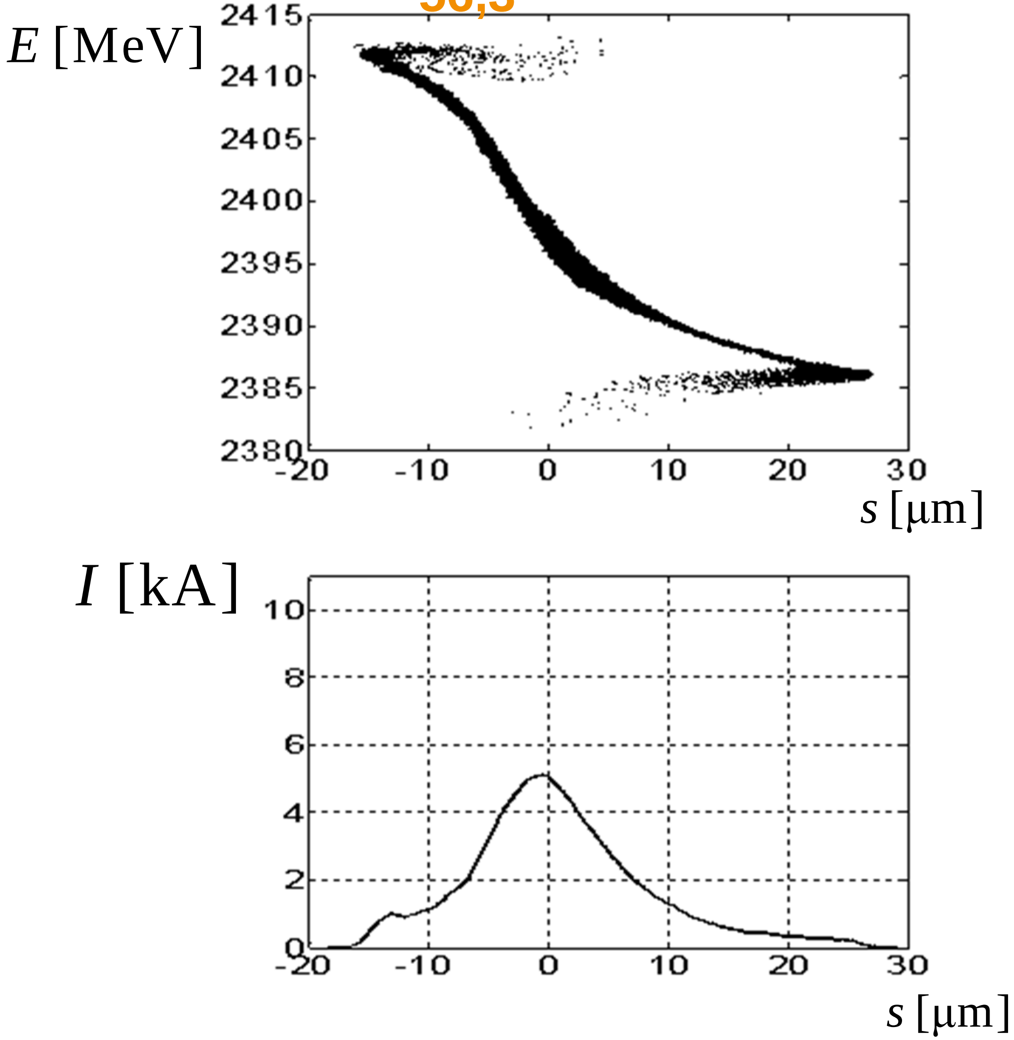
Strong Compression

Q=1 nC

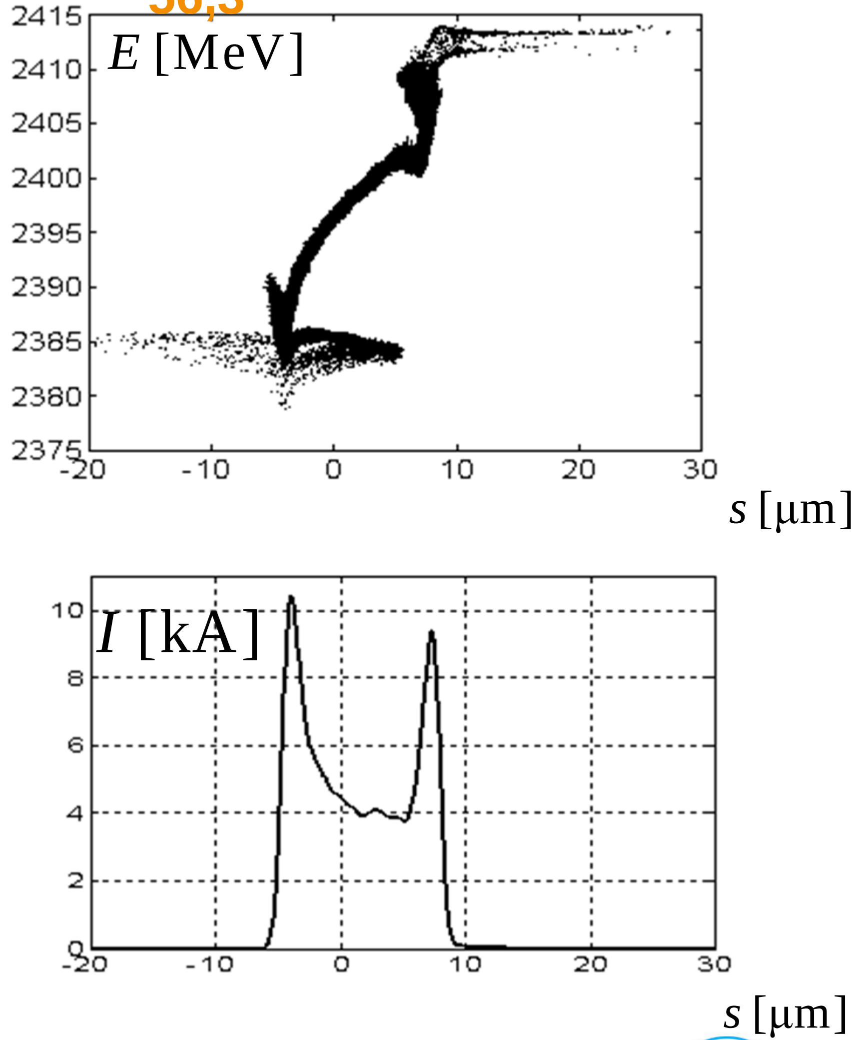
Parameter	Unit		
Bunch charge	nC	1	
Peak current (gun)	A	43	
Compression		116	**228**
Peak current	kA	**5**	**9.8**
Bunch length (FWHM)	fs	178	75
Slice emittance	μm	**1**	**1**
Projected emittance	μm	3.5	8
Slice energy spread (**laser heater off**)	MeV	0.45	1

Strong Compression for 250 pC

$R_{56,3}$= -20 mm



$R_{56,3}$= -23.8 mm



Strong Compression for 250 pC

Macro-parameters

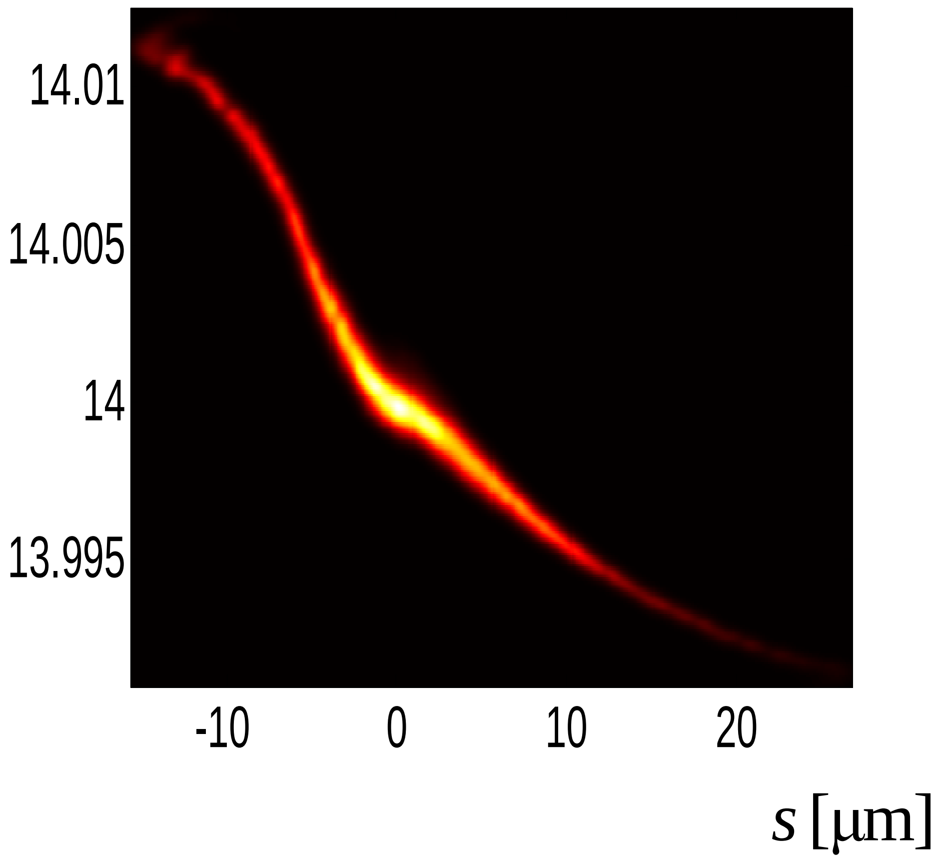
Momentum compaction factor in BC_1 $R_{56,1}$, [mm]	Compr. in BC_1 C_1	Momentum compaction factor in BC_2 $R_{56,2}$, [mm]	Compr. in BC_2 C_2	Momentum compaction factor in BC_3 $R_{56,3}$, [mm]	Total compr. C	Second derivative $(C^{-1})''$, $[m^{-2}]$
-78	3.5	-50	8	**-20,…,-24**	385	1000

$$E_1 = 130\,\text{MeV} \qquad E_2 = 700\,\text{MeV} \qquad E_3 = 2400\,\text{MeV}$$

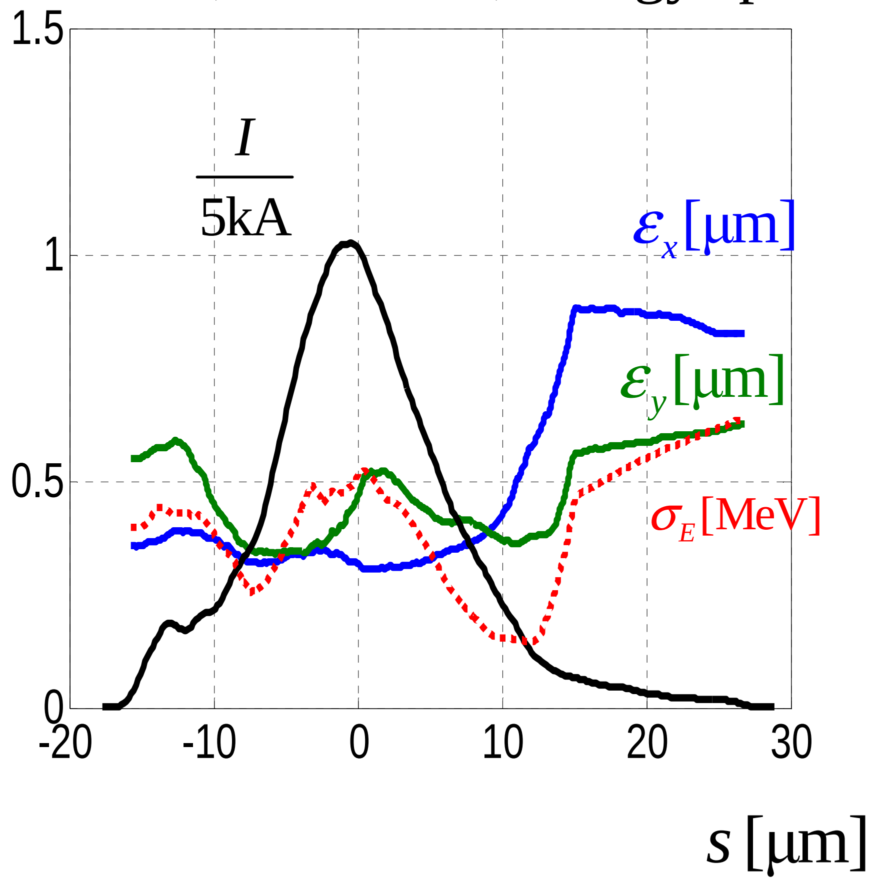
Strong Compression for 250 pC

$R_{56,3}$=-20mm

Phase space



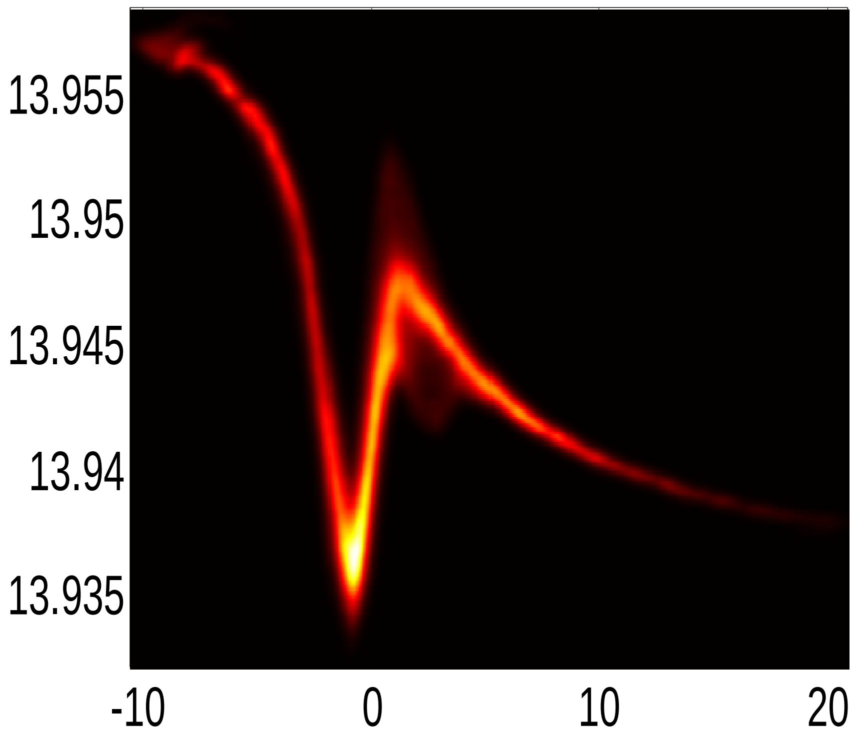
Current, emittance, energy spread



Strong Compression for 250 pC

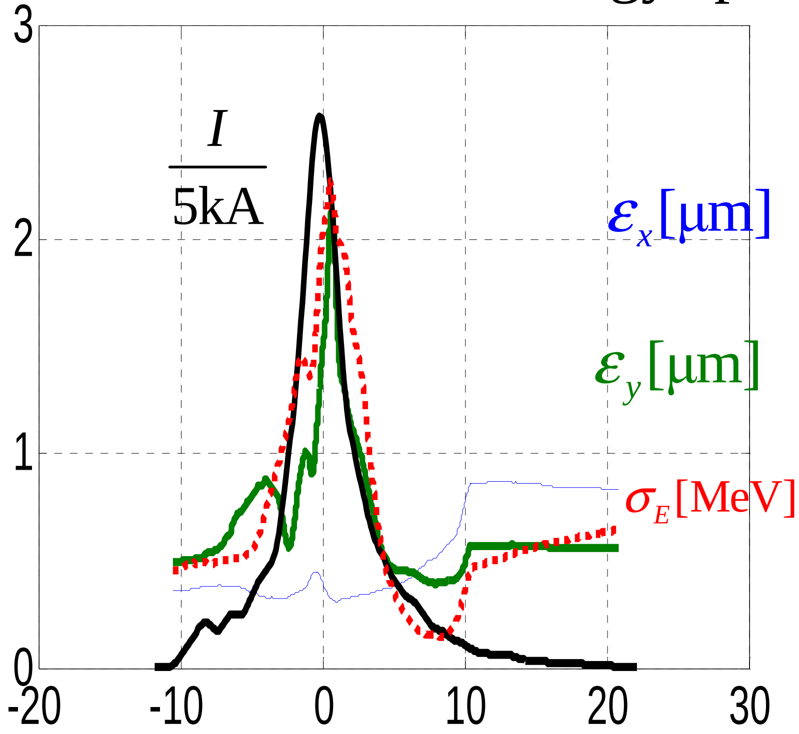
$R_{56,3}$ =-21 mm

Phase space



s [μm]

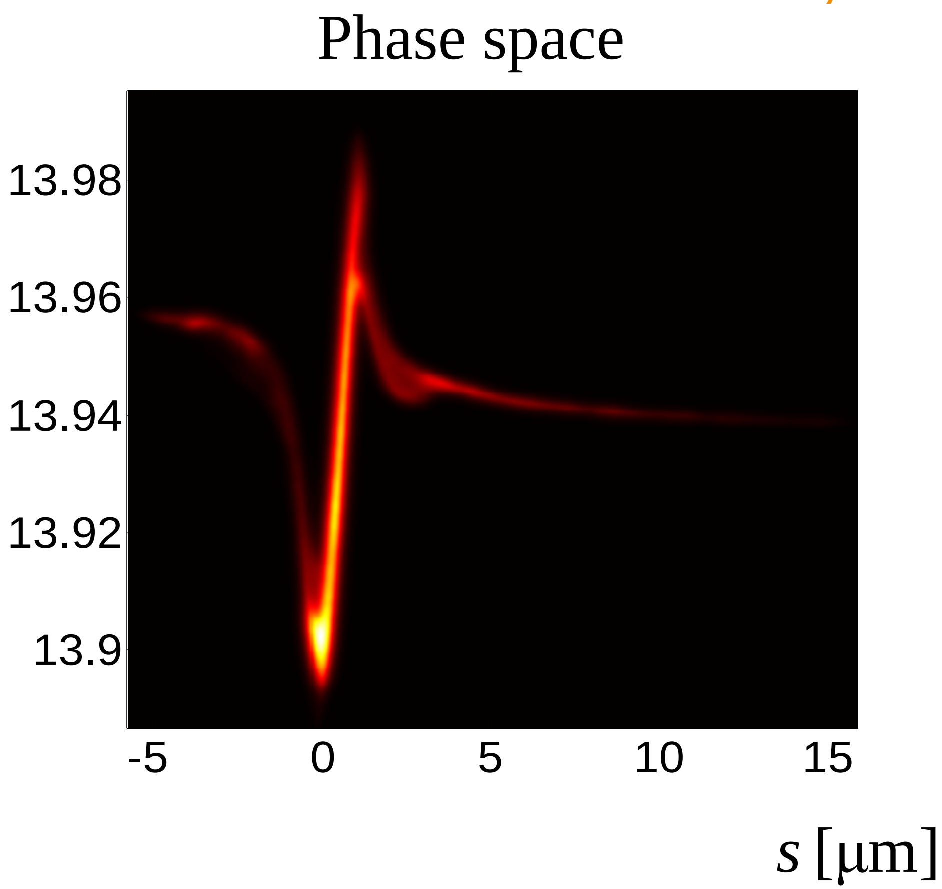
Current, emittance, energy spread

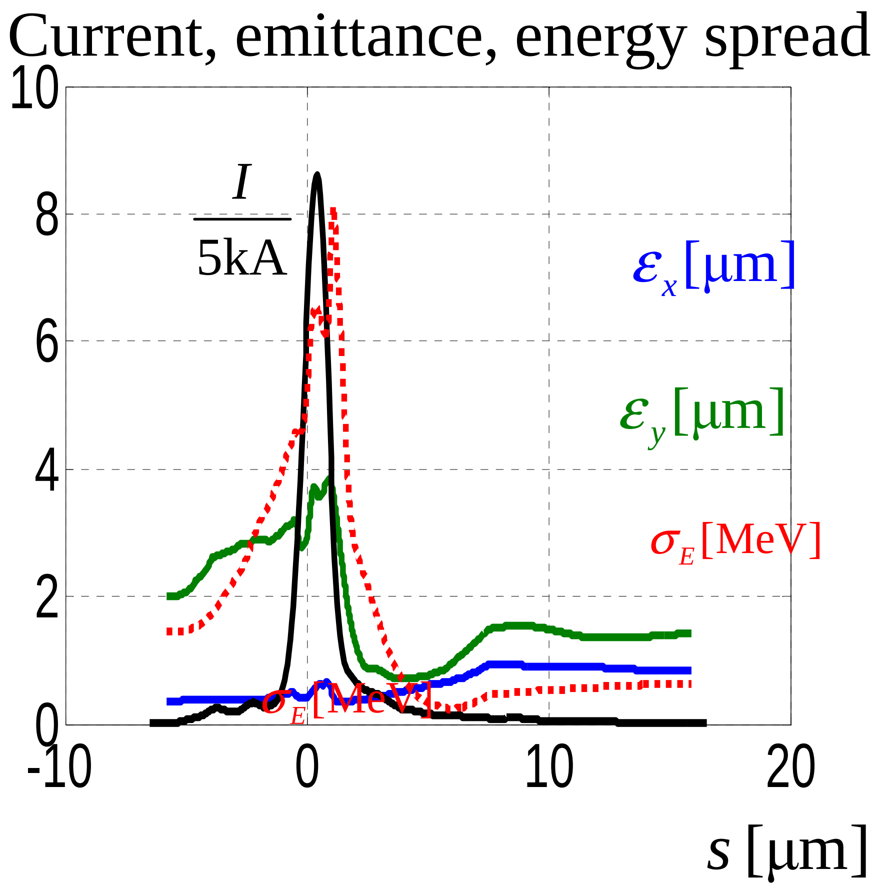


s [μm]

Strong Compression for 250 pC

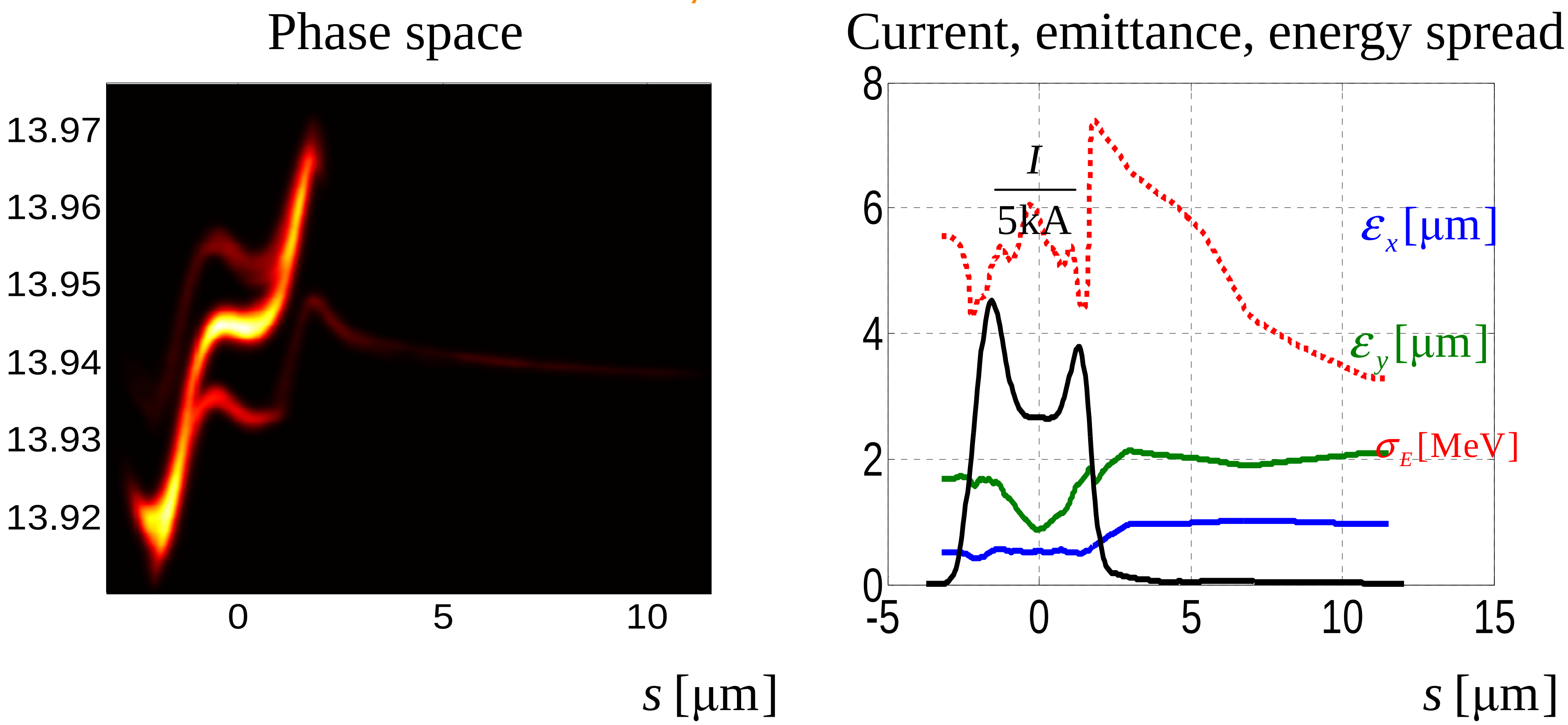
$R_{56,3}$ =-21.9 mm





Strong Compression for 250 pC

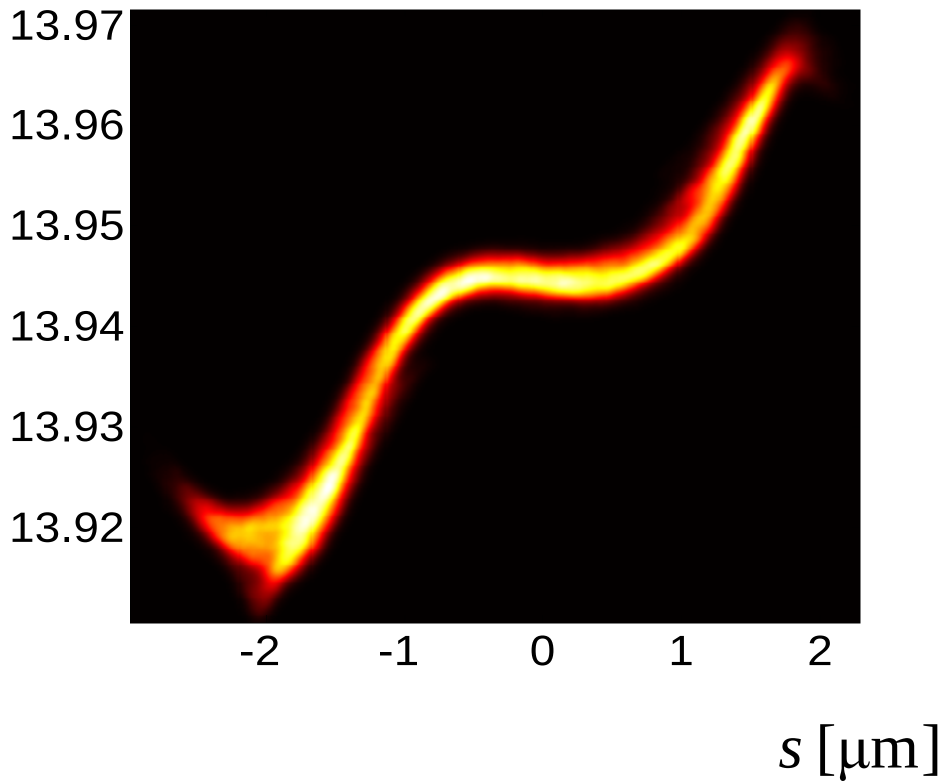
$R_{56,3}$ =-22.6 mm



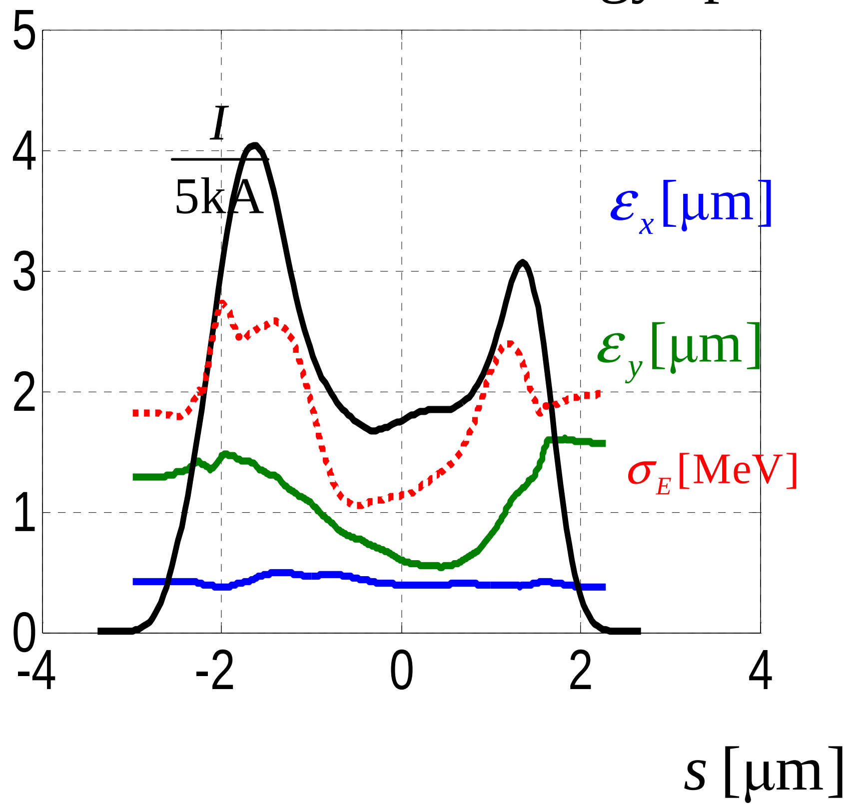
Strong Compression for 250 pC

$R_{56,3}$ =-22.6 mm (70% of particles)

Phase space



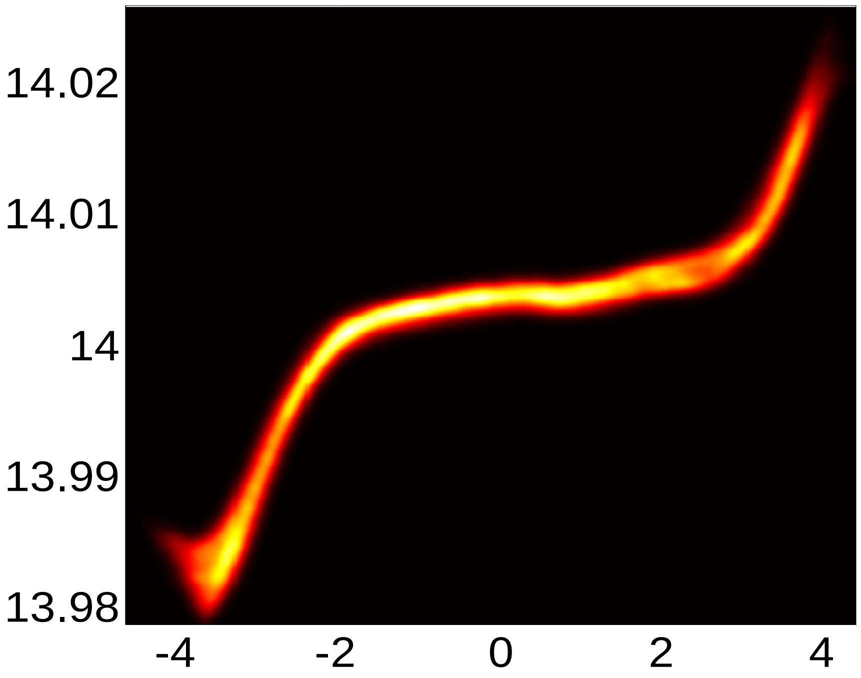
Current, emittance, energy spread



Strong Compression for 250 pC

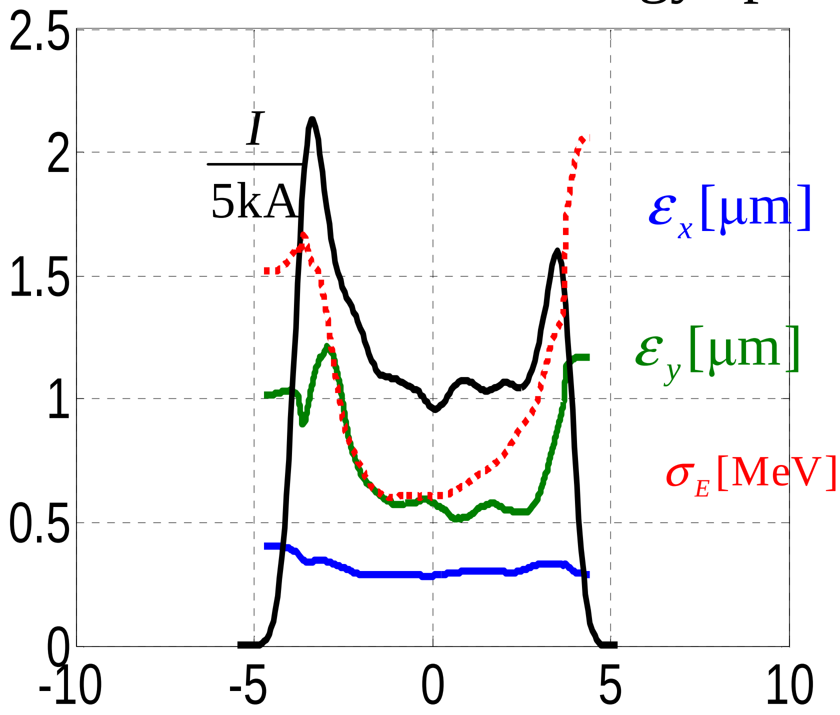
$R_{56,3}$ =-23.2 mm (70% of particles)

Phase space



s [µm]

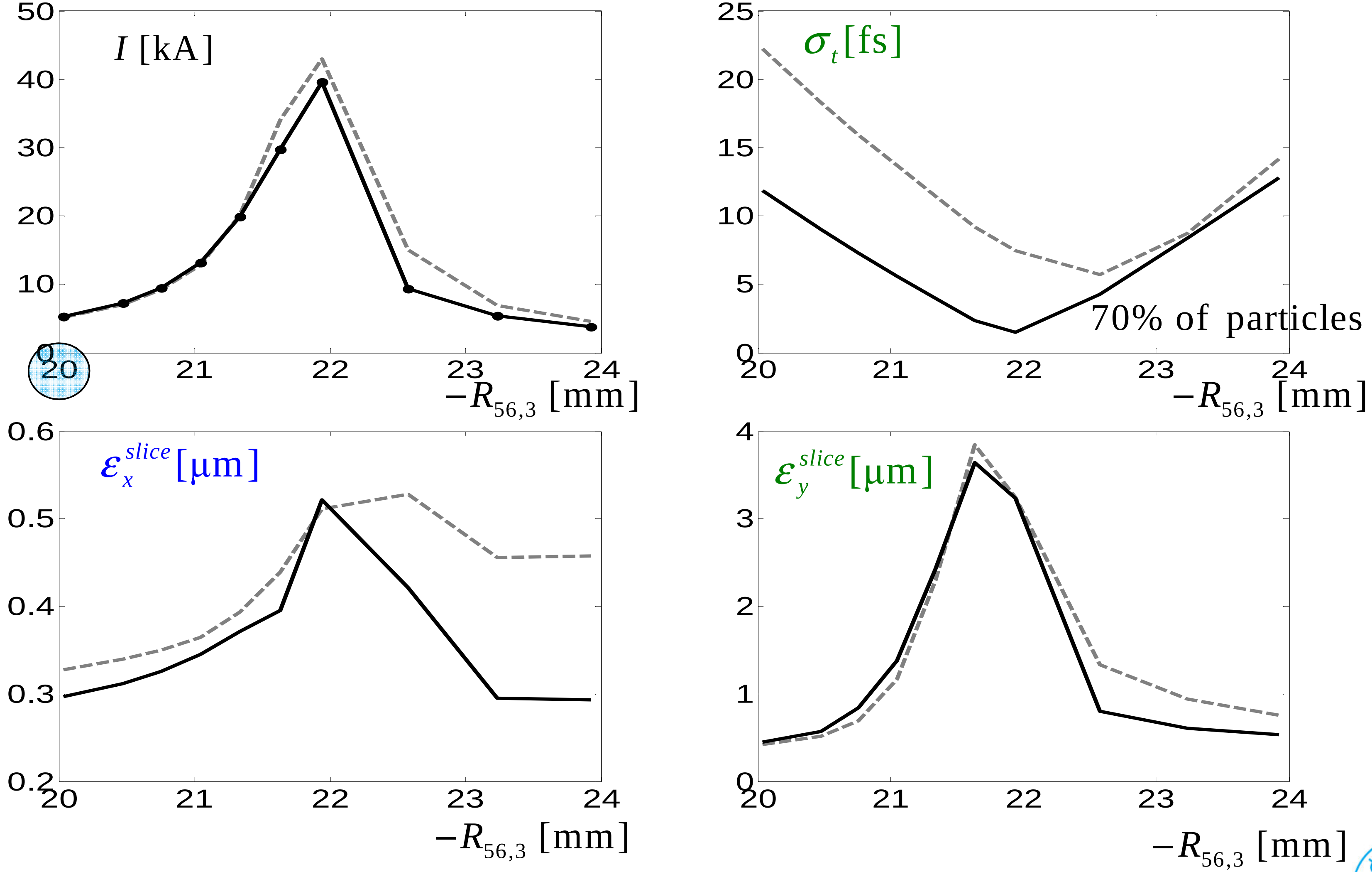
Current, emittance, energy spread



s [µm]

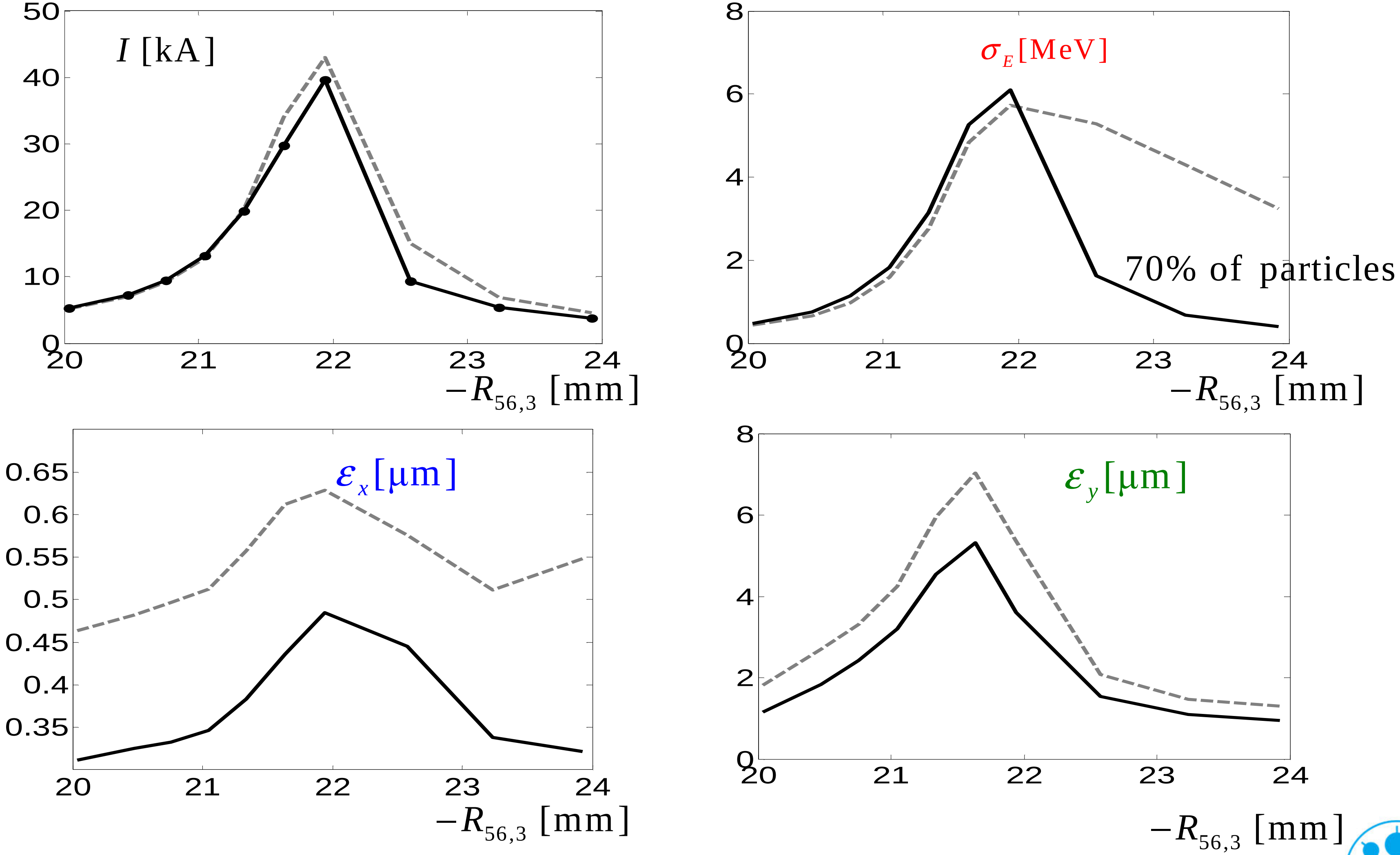
Strong Compression for 250 pC

Beam core parameters vs. R_{56}



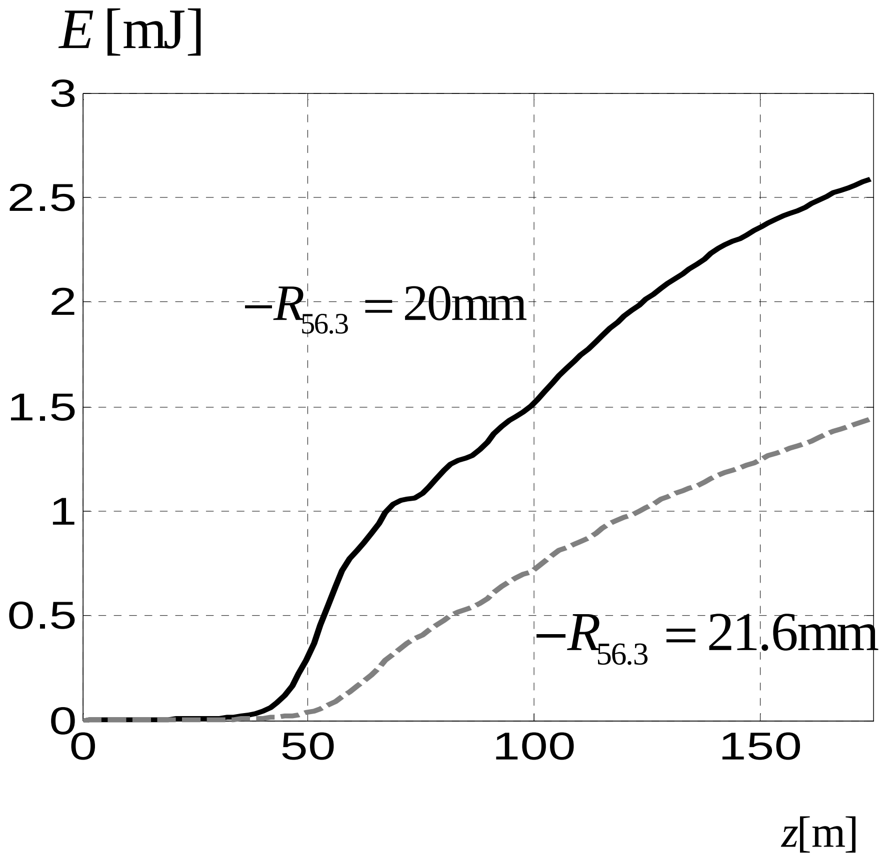
Strong Compression for 250 pC

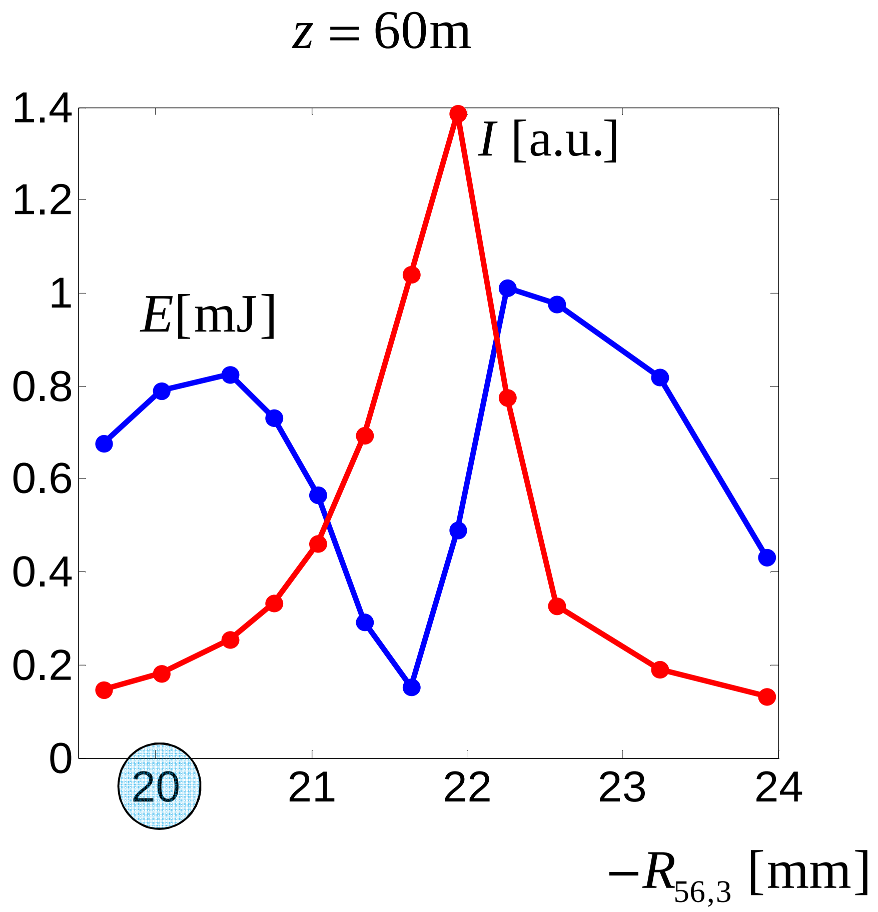
Beam core parameters vs. R_{56}



Strong Compression for 250 pC

Radiation energy vs. R_{56} (with und. wake and taper)

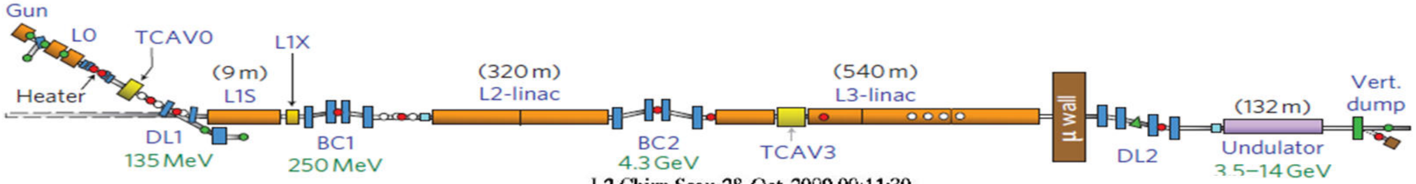


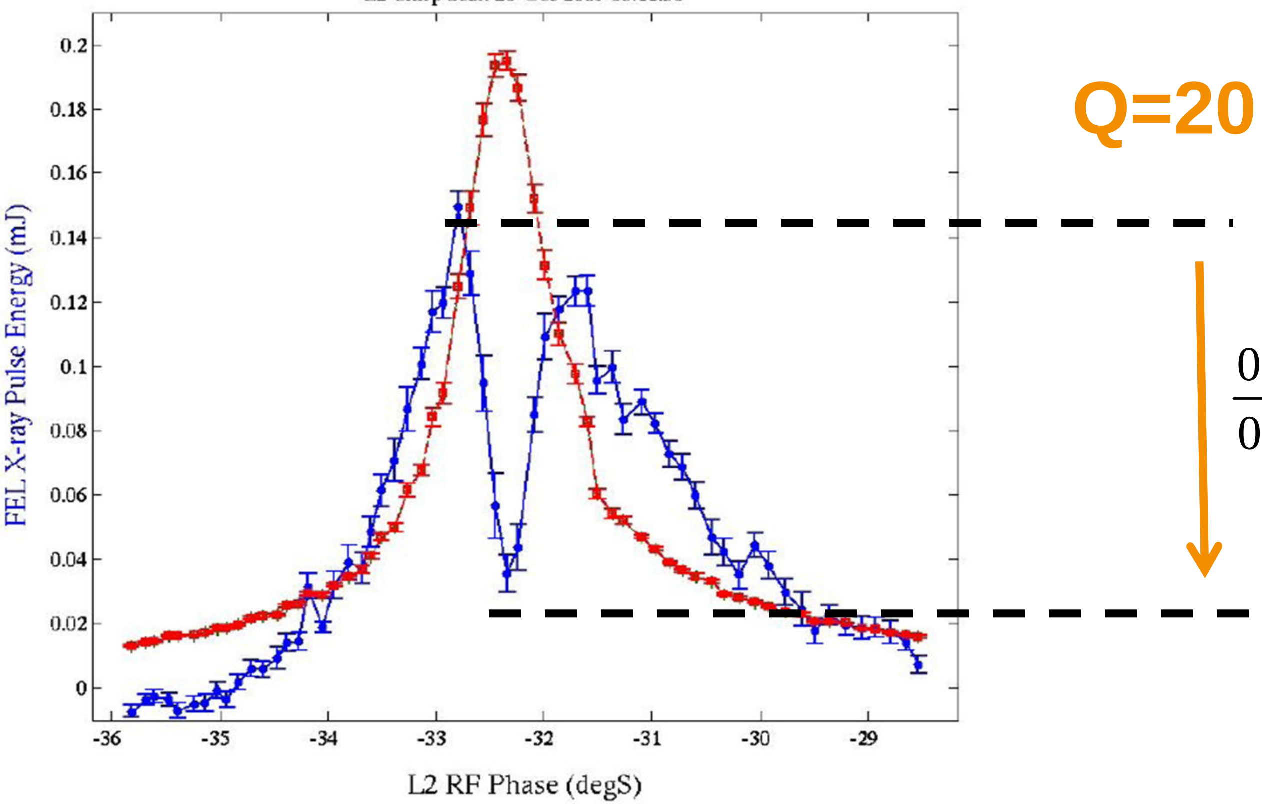


Strong Compression (SLAC)

SLAC-PUB-14234

FEMTOSECOND OPERATION OF THE LCLS FOR USER EXPERIMENTS*



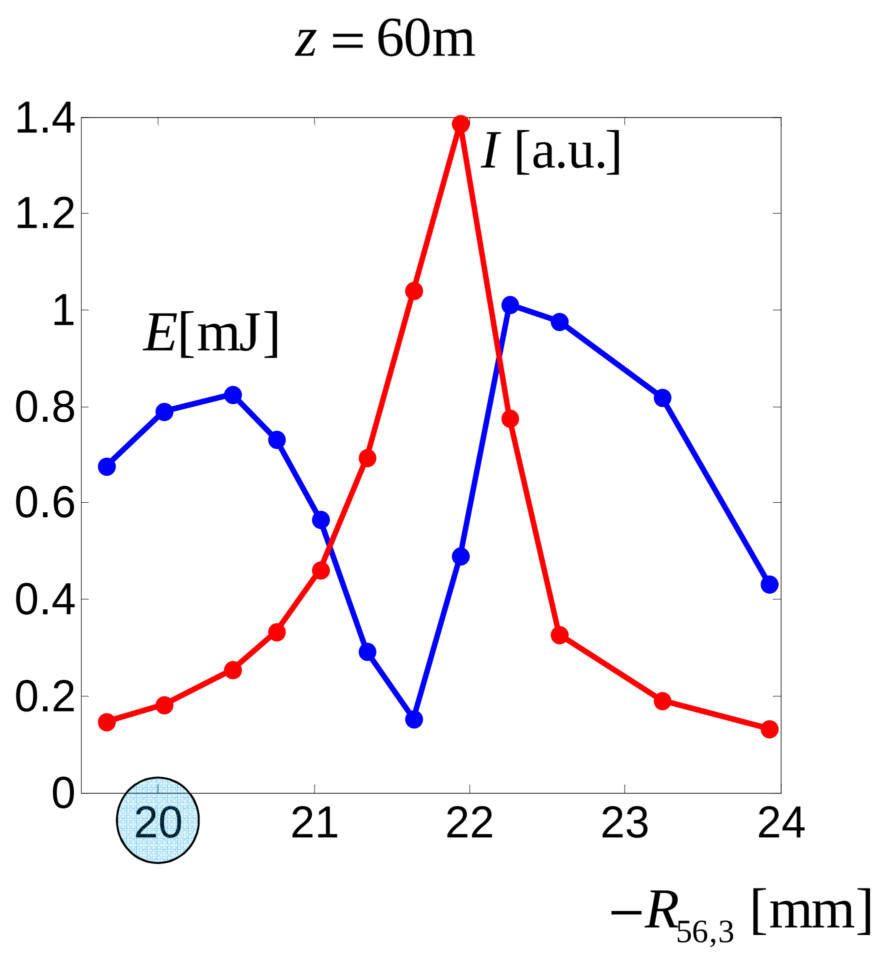


$$\frac{0.15}{0.03} = 5$$

Figure 2: FEL power (blue) and Ipk(red) vs. compression

Strong Compression for 250 pC

Radiation energy vs. compression rate



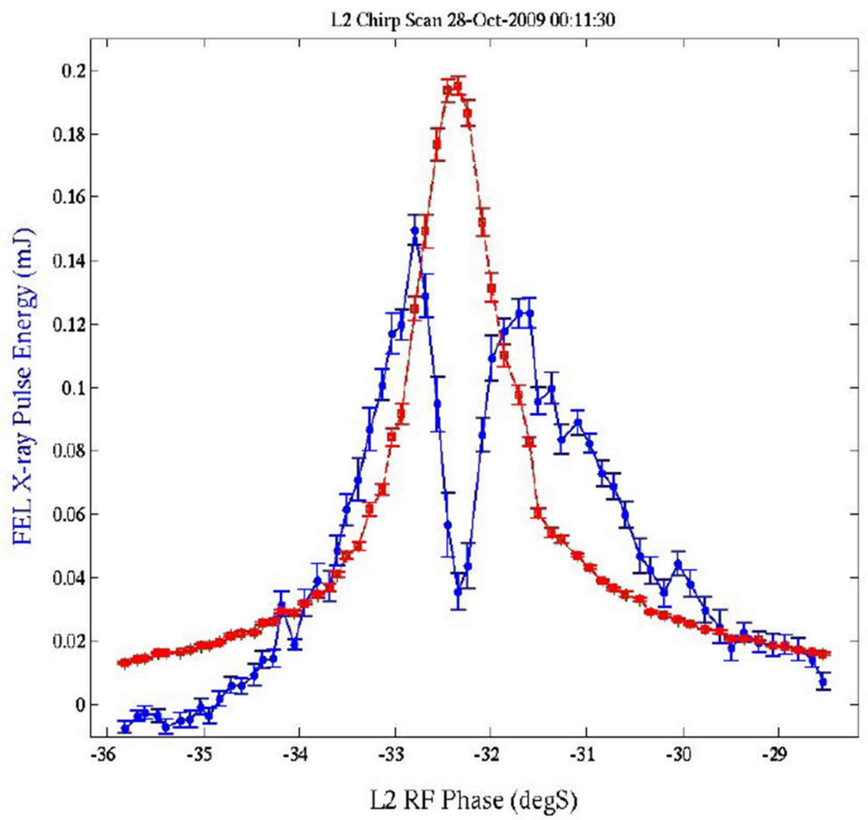
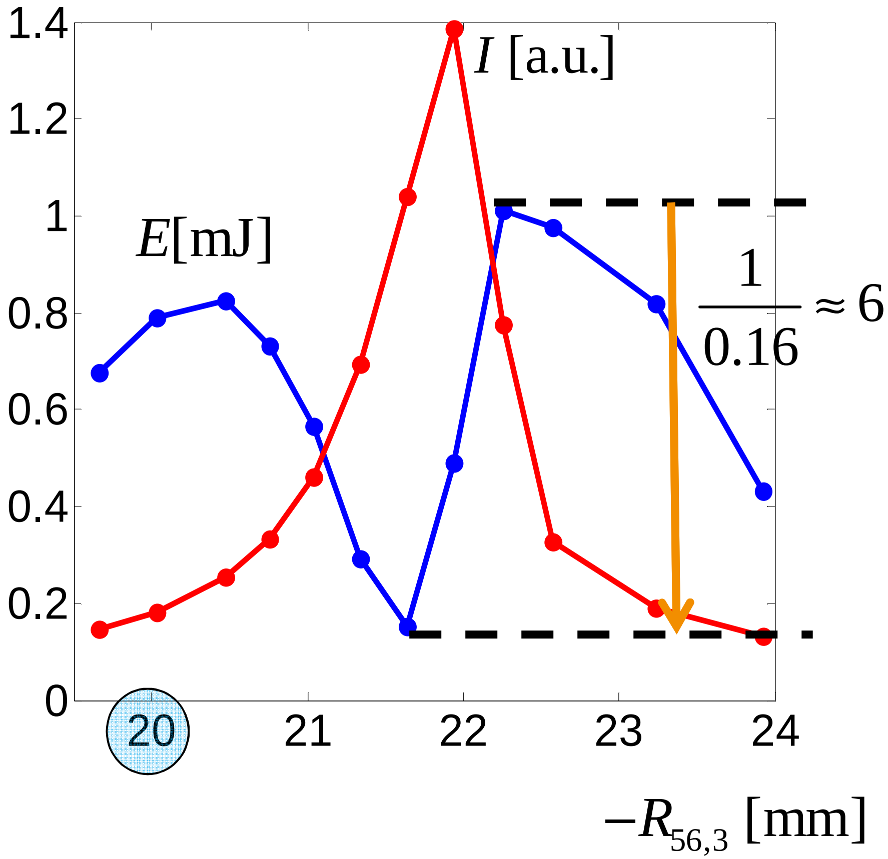


Figure 2: FEL power (blue) and Ipk(red) vs. compression

Strong Compression for 250 pC

Radiation energy vs. compression rate

$z = 60\text{m}$



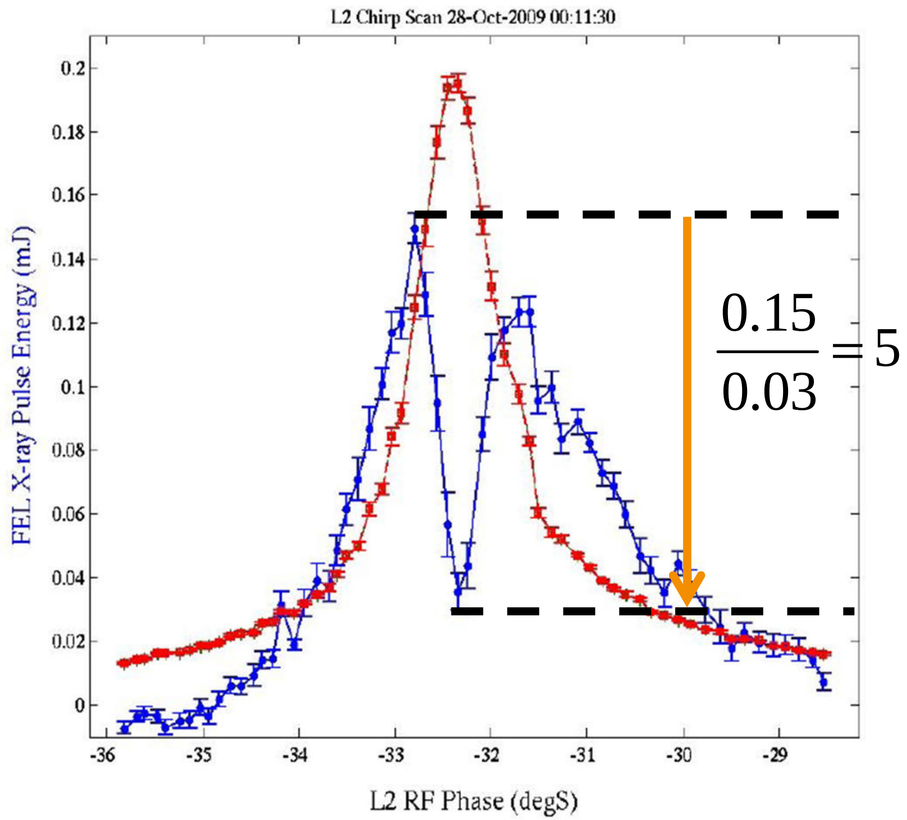
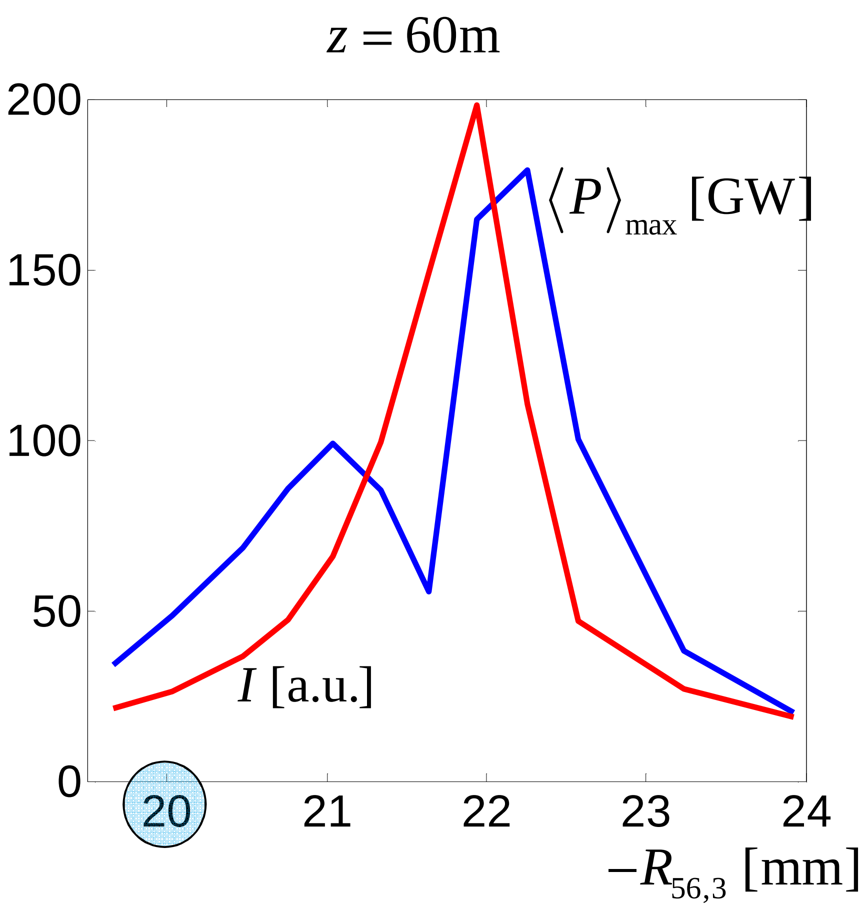
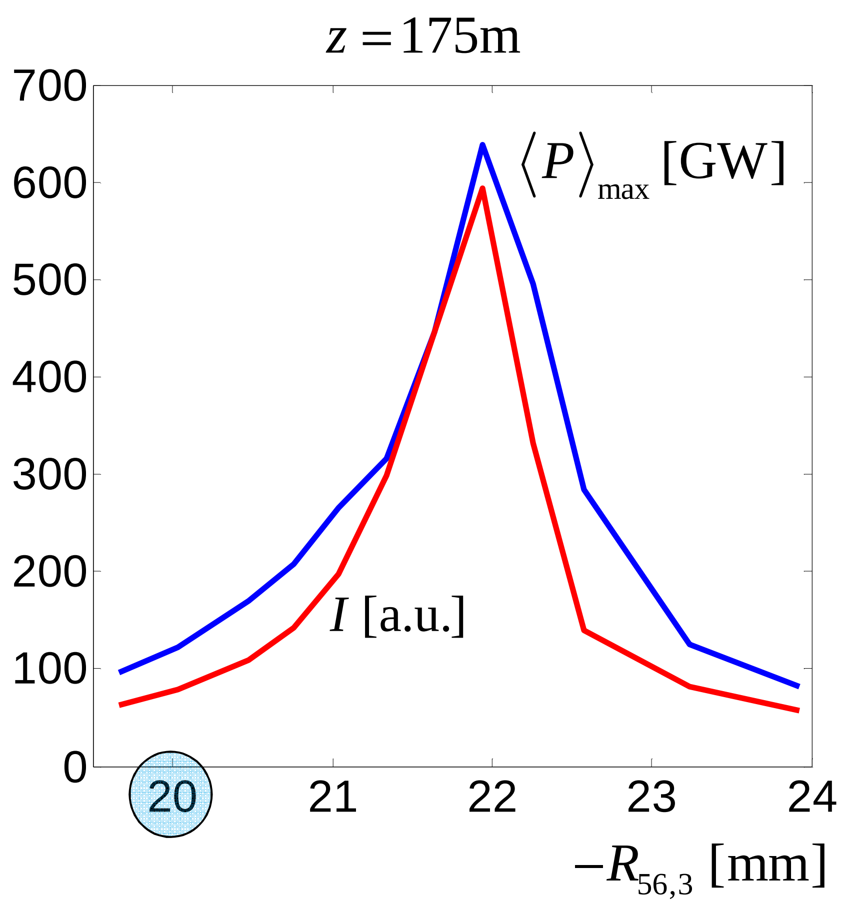


Figure 2: FEL power (blue) and Ipk(red) vs. compression

Strong Compression for 250 pC

Radiation power vs. compression rate





Summary

- Bunches with charge 20-1000 pC can be compressed to 5 kA and higher
- Radiation energy drops down at “full” compression
- Overcompression scenario can be used

Acknowledgements
to M.Dohlus and T.Limberg for many useful discussions