Beam Dynamics and FEL Simulations for FLASH

Igor Zagorodnov and Martin Dohlus

08.02.2010

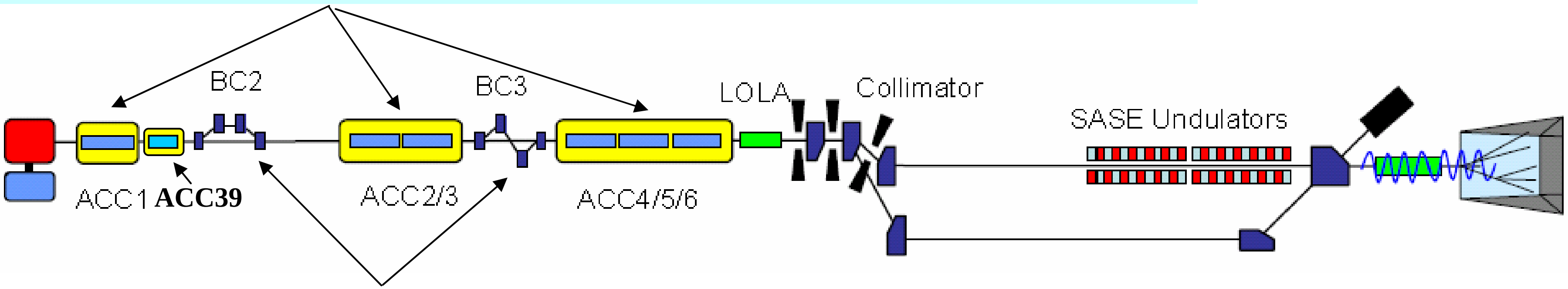
Beam Dynamics Meeting, DESY

FLASH I parameters

FLASH I layout is considered. But the results are equally applicable for FLASH II (SASE).

short radiation wavelength $\lambda \sim \frac{1}{\gamma^2}$ ← high electron energy

In accelerator modules ACC1, ACC2,..., ACC6 the **energy** of the electrons is increased from 5 MeV (gun) to **1000 MeV** (undulator). → λ~ 6.5 nm



In compressors **the peak current *I*** is increased from 1.5-50 A (gun) to **2500 A** (undulator).

short gain length $L_g \sim \frac{\varepsilon^{5/6}}{\sqrt{I}}\left(1+O(\sigma_E{}^2)\right)$ (for the optimal beta function)

high peak current

FLASH I parameters

small emittance

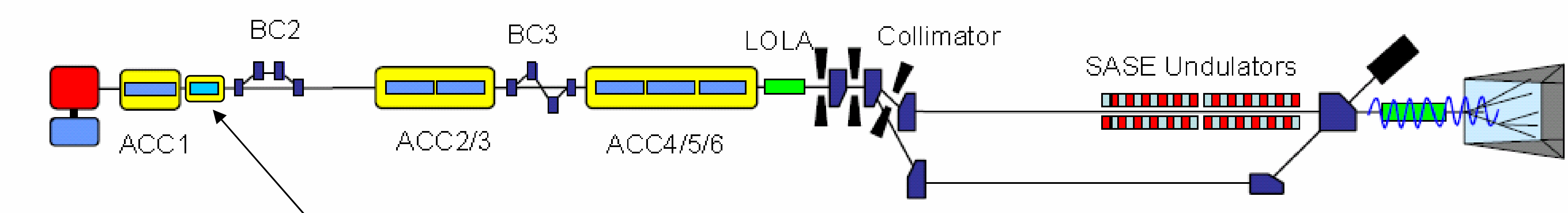
short gain length $$L_g \sim \frac{\varepsilon^{5/6}}{\sqrt{I}}\left(1+O(\sigma_E{}^2)\right)$$ (for the optimal beta function)

small energy spread

high peak current

Electron beam properties for good lasing

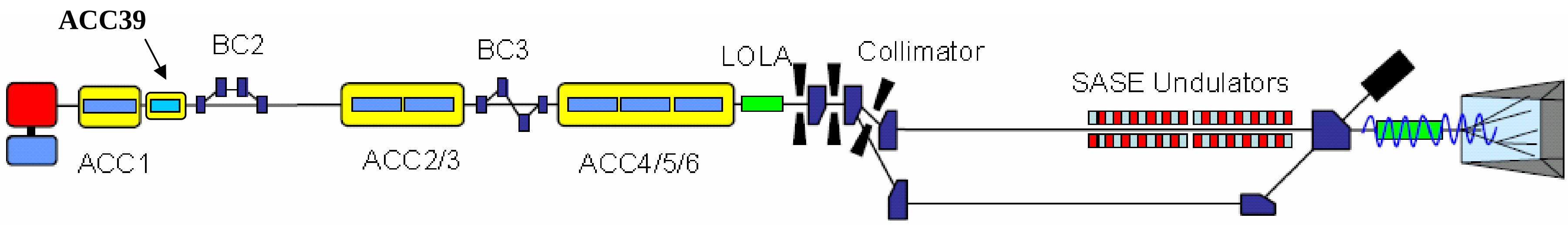
High **peak current** ~ **2500 A.**
Small slice **emittance** ε (**0.4-1 μm**).
Small slice **energy spread** σ_E (**< 300 keV**).



High harmonic module in 2010

FLASH I parameters

energy 1 GeV
radiation wavelength ~ 6.5 nm



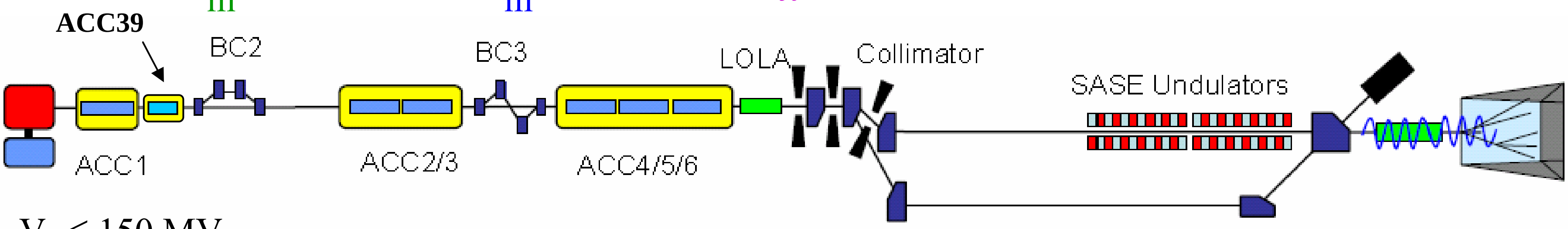
Only **SASE mode** of operation is investigated.
Charge tuning (20-1000 pC) allows to tune

- the radiation **pulse energy (30-1400 μJ)**,
- the **pulse width** FWHM (**2-70 fs**).

FLASH I parameters

Technical constrains

$1.4 \le \frac{r_1}{\mathrm{m}} \le 1.93$ $5.3 \le \frac{r_2}{\mathrm{m}} \le 16.8$ $r_{56} \approx 0 \ldots -0.56$ mm



$V_1 \le 150$ MV

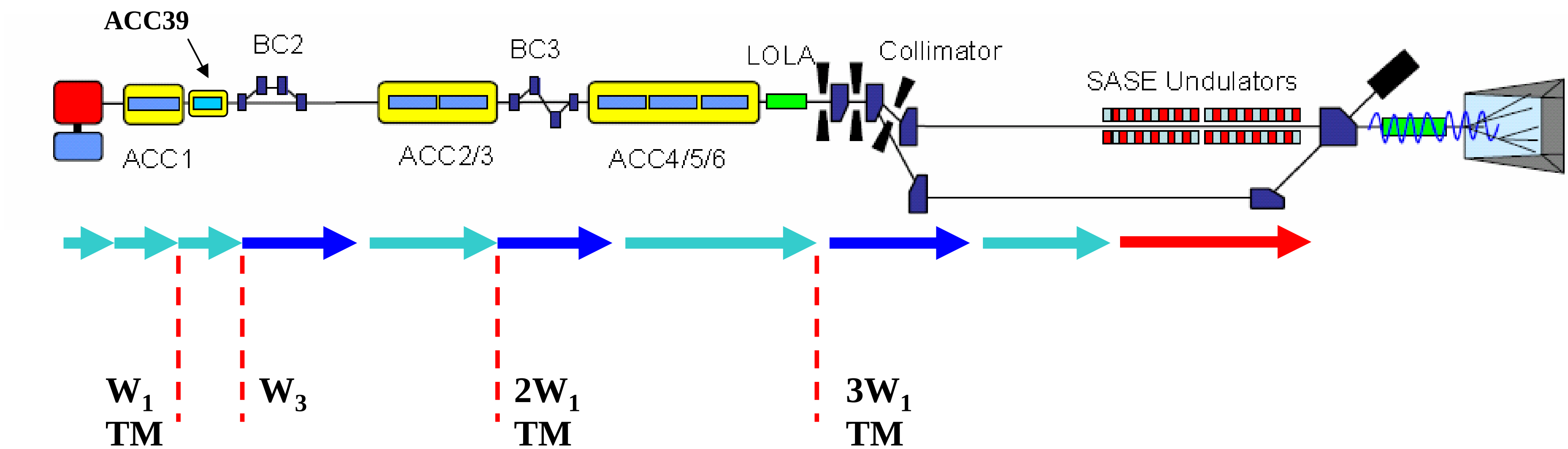
$V_{39} \le 26$ MV

$V_2 \le 360$ MV

How to provide (1) a well conditioned electron beam and (2) what are the properties of the radiation?

(1) Self consistent beam dynamics simulations.
(2) FEL simulations.

FLASH I
3d simulation method (self-consistent)



ASTRA (tracking with space charge, DESY)

CSRtrack (tracking through dipoles, DESY)

ALICE (3D FEL code, DESY)

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 (V2+, V.Balandin &N.Golubeva)

FLASH I
simulation methods (looking for working points)

1d analytical solution without collective effects
(8 macroparameters -> 6 RF settings)

initial guess

1d tracking with space charge and wakes

~ **seconds**
(1 cpu)

- accelerator: $E_1(s_1) = E_0(s_0) + V\cos(ks_0 + \varphi)$, $s_1 = s_0$
- compressor: $E_1(s_1) = E_0(s_0)$, $s_1(s_0) = s_0 + (r_{56}\delta + t_{566}\delta^2 + u_{5666}\delta^3)$

~ 5 iterations

quasi 3d tracking with all collective effects

~ **30 min**
(1 cpu)

- accelerator: $E_1(s_1) = E_0(s_0) + V\cos(ks_0 + \varphi)$, $s_1 = s_0$, matrix transport for x & y
- **CSRtrack**

~ 5 iterations

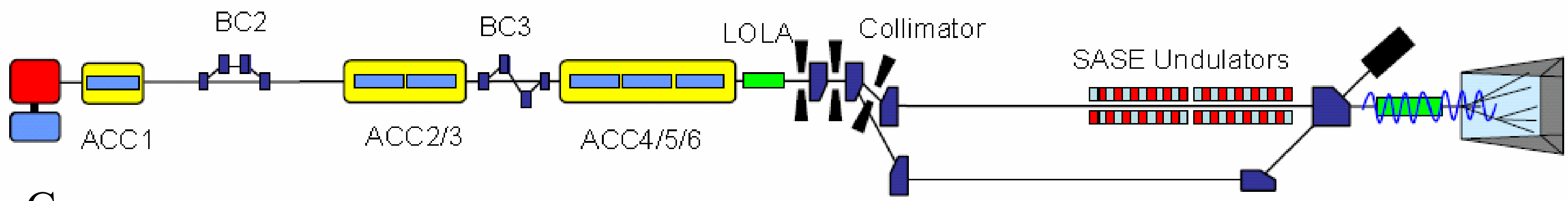
3d tracking with all collective effects

~ **10 h**
(46 cpu-s)

- **Astra**
- **CSRtrack**

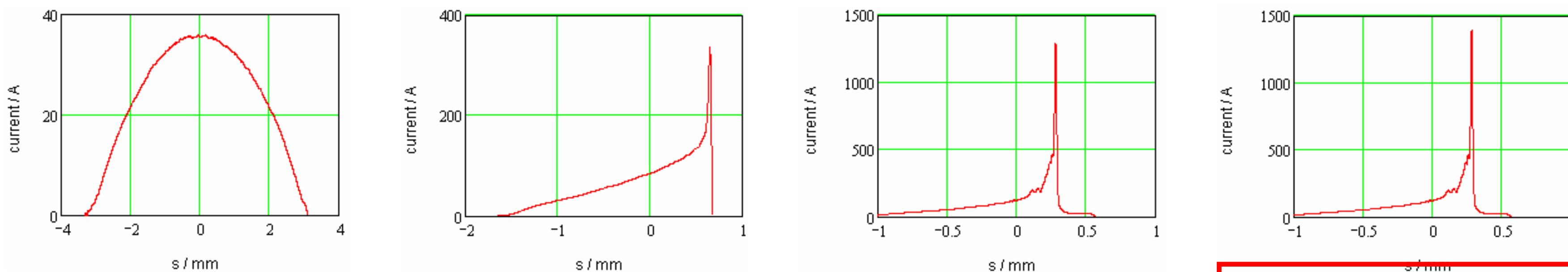
final result

FLASH I before and after upgrade
rollover compression vs. linearized compression

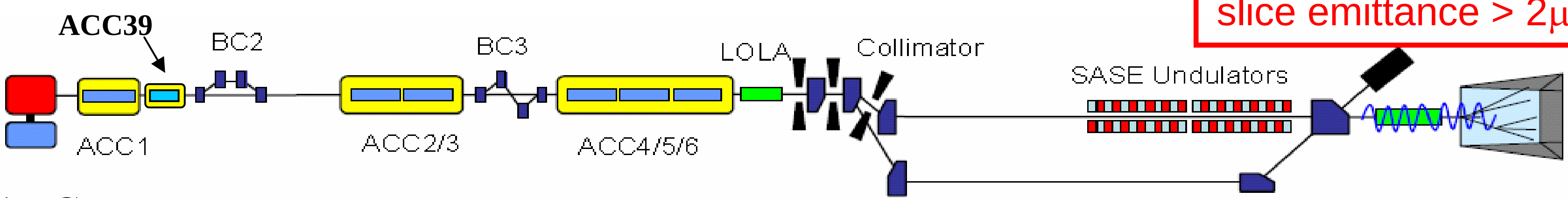


Q=0.5 nC

~ 1.5 kA

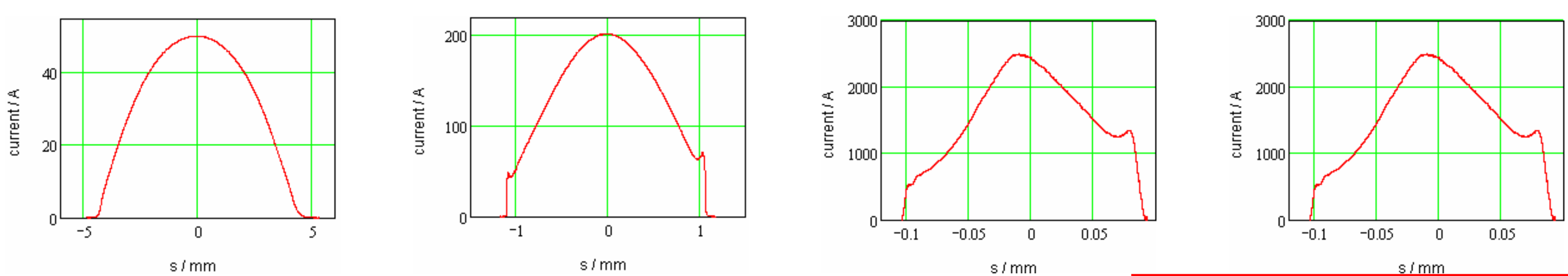


slice emittance > 2μm



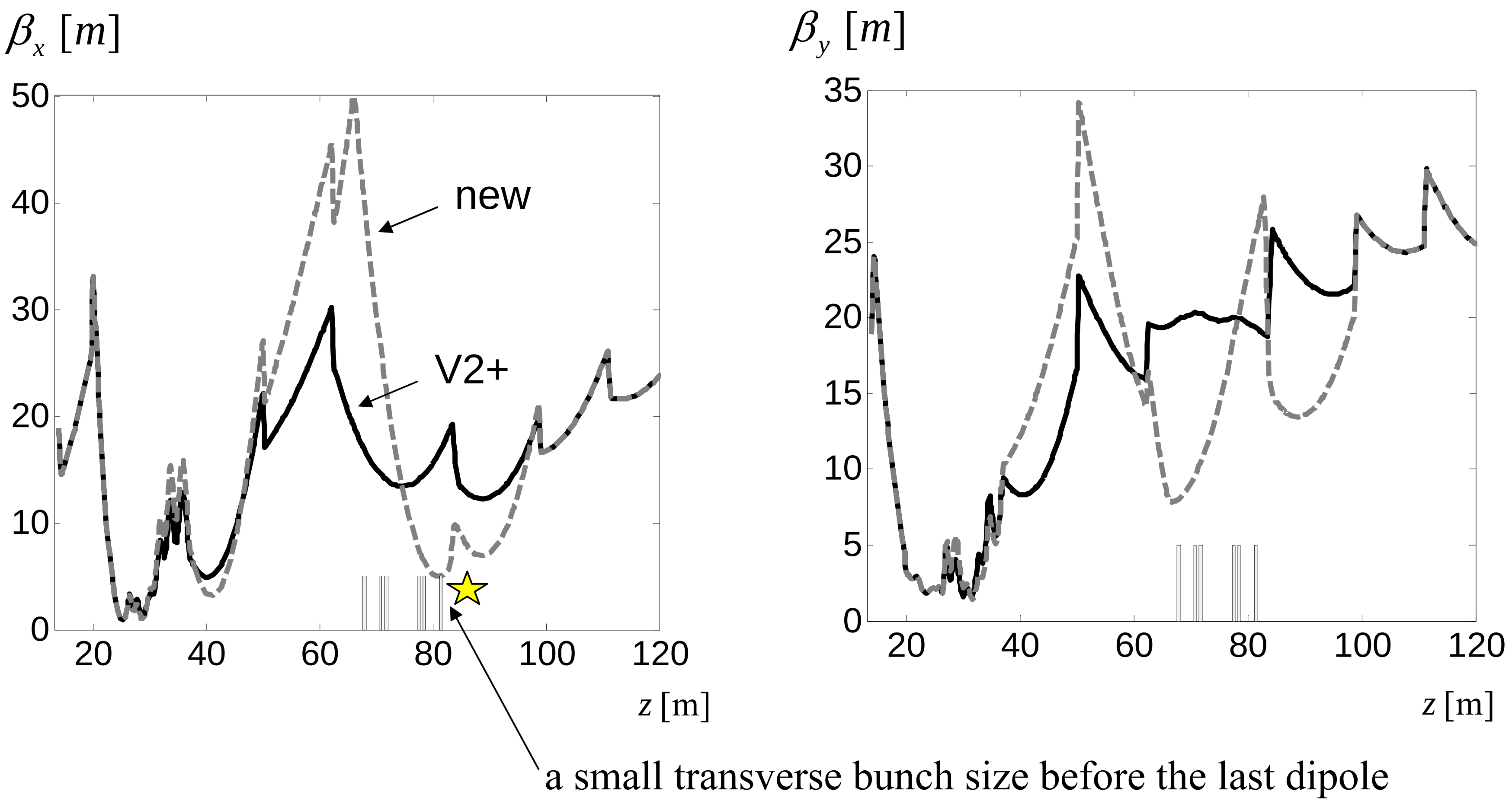
Q=1 nC

~2.5 kA



slice emittance ~ 0.3 - 1μm

Optics correction

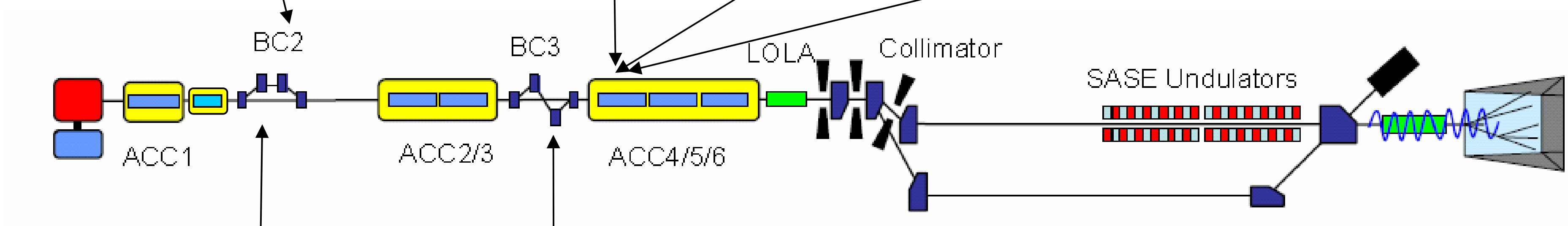


M.Dohlus, T. Limberg, *Impact of optics on CSR-related emittance growth in bunch compressor chicanes*, PAC 05, 2005

Working points (8 macroparameters)

$$C_1^{-1} \equiv \frac{\partial s_1}{\partial s}(0) \qquad C^{-1} \equiv \frac{\partial s_2}{\partial s}(0) \qquad p_1 \equiv \partial_s C^{-1} \qquad p_2 \equiv \partial_s^2 C^{-1}$$

?



E_1	E_2
r_1	r_2

s - particle position before BC2

s_1 - particle position between BC2 and BC3

s_2 - particle position after BC3

$s=s_1=s_2=0$ for the reference particle

What is the optimal choice?

Working points (8 macroparameters)

What is the optimal choice?

$V_1 \le 150$ MV

5% reserve

$$E_1 = E_0 + 0.95 eV_1 \left(1 - \left(\frac{\omega}{\omega_3} \right)^2 \right) = 5\text{MeV} + 0.95 \frac{8}{9} 150\text{MeV} \approx 130\text{MeV}$$

$$E_1 = 130\text{MeV}$$

$V_2 \le 360$ MV

10% reserve

$$E_2 = E_1 + eV_2 \cdot 0.9 \approx 450 \text{ MeV}$$

$$E_2 = 450\text{MeV}$$

$E_1 = ?$
$\mathrm{E}_2 = ?$
$r_1 = ?$
$r_2 = ?$
$C = ?$
$C_1 = ?$
$\partial_s C^{-1} = ?$
$\partial_s^2 C^{-1} = ?$

Working points (8 macroparameters)

$$1.4 \le \frac{r_1}{\mathrm{m}} \le 1.93$$

- low compression in BC1 and high compression in BC2

- maximal energy chirp transported through BC1for the same C_1 (it looses the voltage requirements on RF system ACC2/ACC3)

$$r_1 = 1.93\mathrm{m}$$

$$I_0 = 52\mathrm{A} \qquad I_f = 2500\mathrm{A}$$

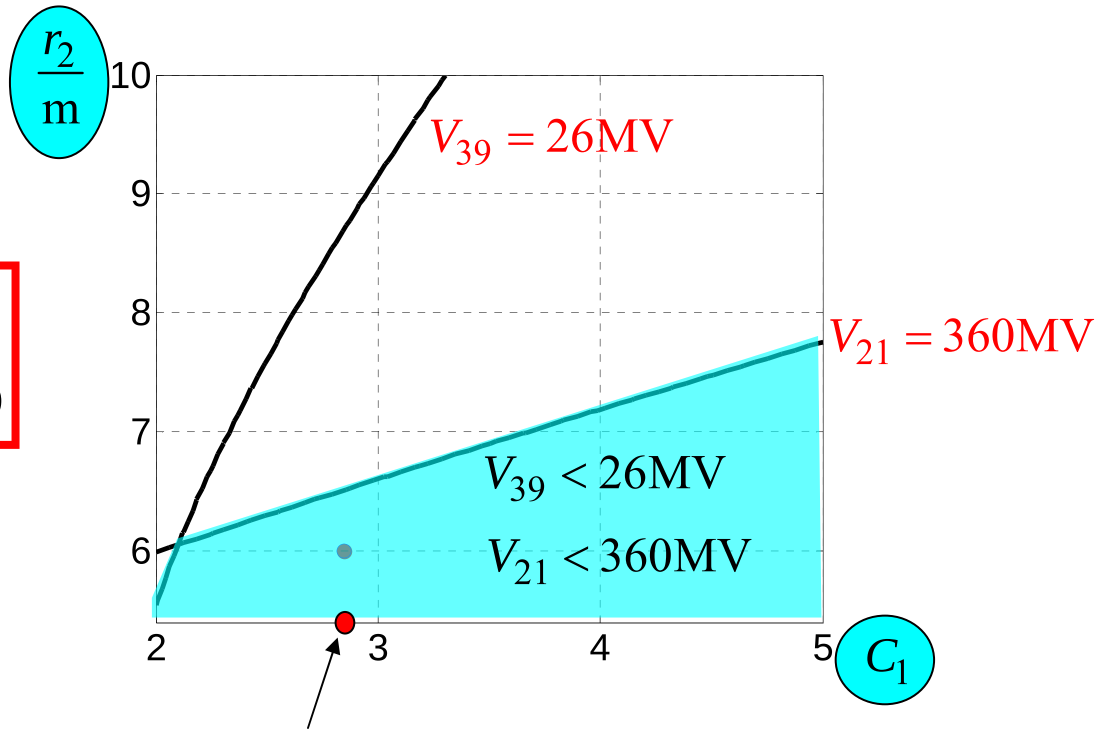
$$C = \frac{I_f}{I_0} = 48$$

$E_1 = 130\mathrm{MeV}$
$\mathrm{E}_2 = 450\mathrm{MeV}$
$r_1 = ?$
$r_2 = ?$
$C = ?$
$C_1 = ?$
$\partial_s C^{-1} = ?$
$\partial_s^2 C^{-1} = ?$

Working points (8 macroparameters)

$$p_1 = \partial_s C^{-1} = 0$$

$$p_2 = \partial_s^2 C^{-1} = 0$$



$$E_1 = 130\text{MeV}$$

$$\text{E}_2 = 450\text{MeV}$$

$$r_1 = 1.93\text{m}$$

$$r_2 = ?$$

$$C = 48$$

$$C_1 = ?$$

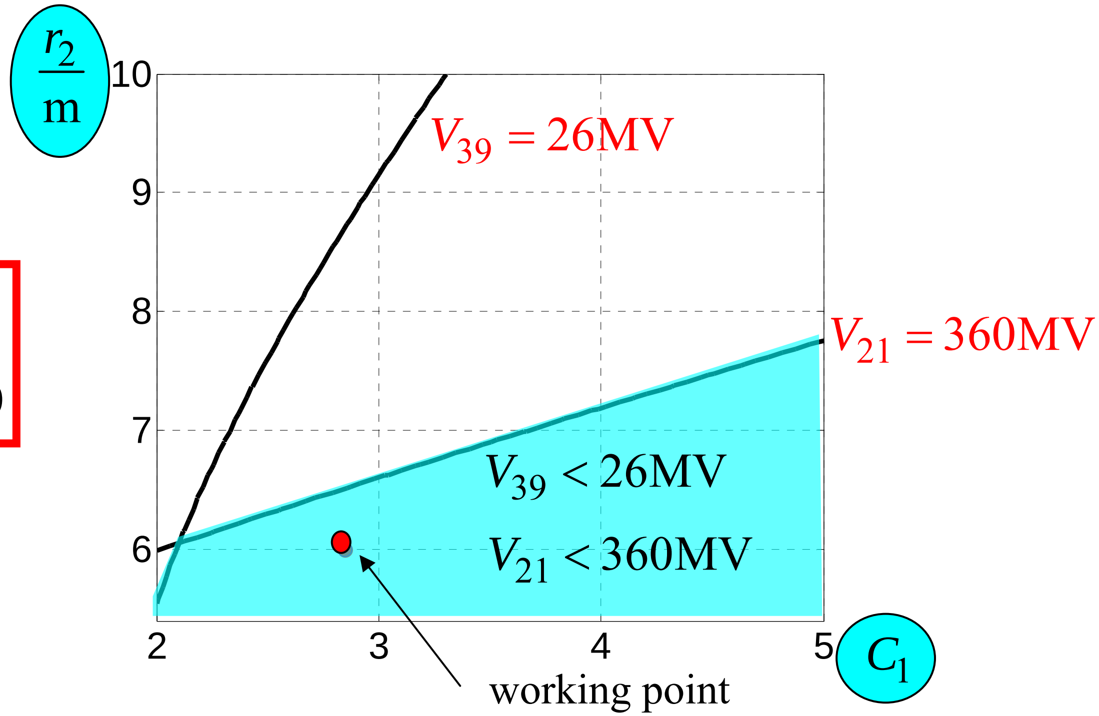
$$\partial_s C^{-1} = ?$$

$$\partial_s^2 C^{-1} = ?$$

$$C_1 > 2$$

$$C_1 = 2.84$$

Working points (8 macroparameters)



$$p_1 = \partial_s C^{-1} = 0$$
$$p_2 = \partial_s^2 C^{-1} = 0$$

$$E_1 = 130\mathrm{MeV}$$
$$\mathrm{E}_2 = 450\mathrm{MeV}$$
$$r_1 = 1.93\mathrm{m}$$
$$r_2 = ?$$
$$C = 48$$
$$C_1 = 2.84$$
$$\partial_s C^{-1} = ?$$
$$\partial_s^2 C^{-1} = ?$$

$$\varphi_2 = \mathrm{acos}\left(\frac{E_2 - E_1}{\max(V_2)\cdot 0.95}\right) \approx 22^o$$

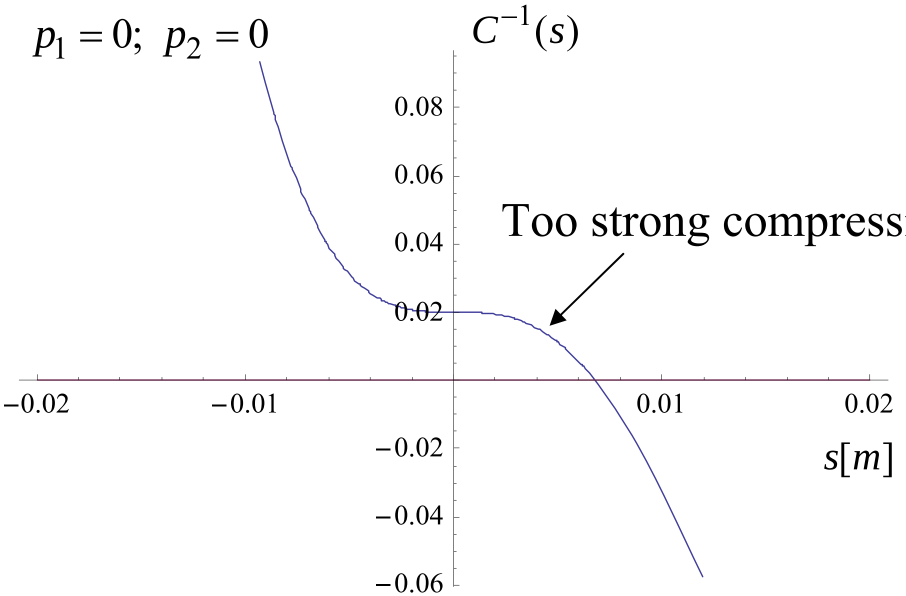
5% reserve

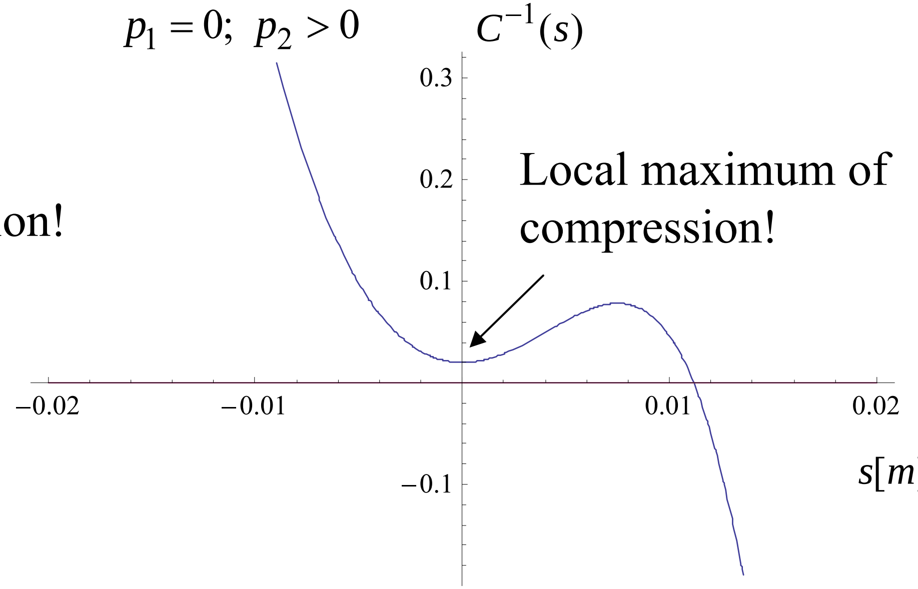
$$r_{562} = \frac{(C_2 - 1) r_{561}}{C_2((C_1 - 1) E_{10} E_{20}^{-1} - g)} \qquad g = k\frac{V_2}{E_{20}} r_{562} \sin\varphi_2$$

$$r_2 \approx \frac{L_B}{\sin\sqrt{-r_{562}/(3L_B + 4L_D)}}$$

$$r_2 = 6\mathrm{m}$$

Working points (8 macroparameters)





$p_2 > 0$

$E_1 = 130\text{MeV}$

$E_2 = 450\text{MeV}$

$r_1 = 1.93\text{m}$

$r_2 = 6\text{m}$

$C = 48$

$C_1 = 2.84$

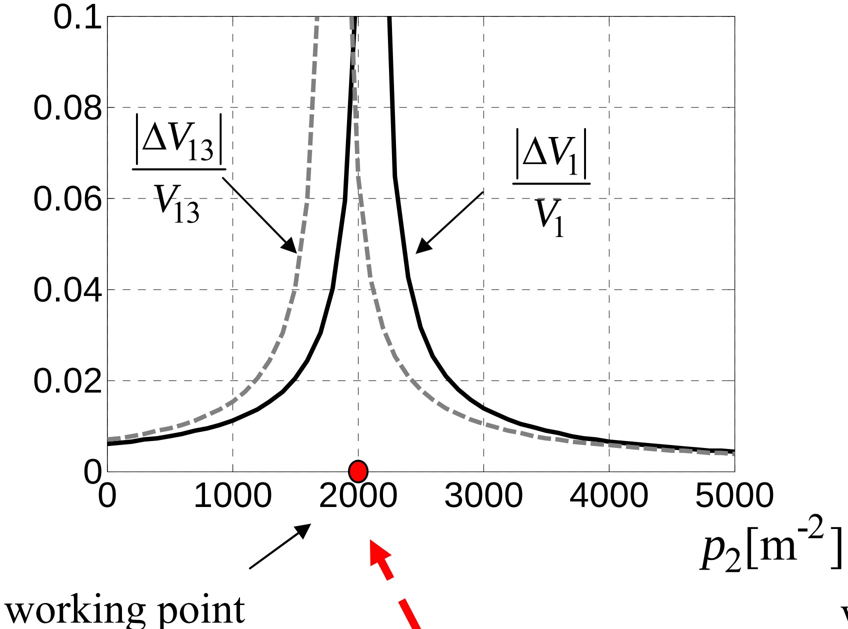
$\partial_s C^{-1} = ?$

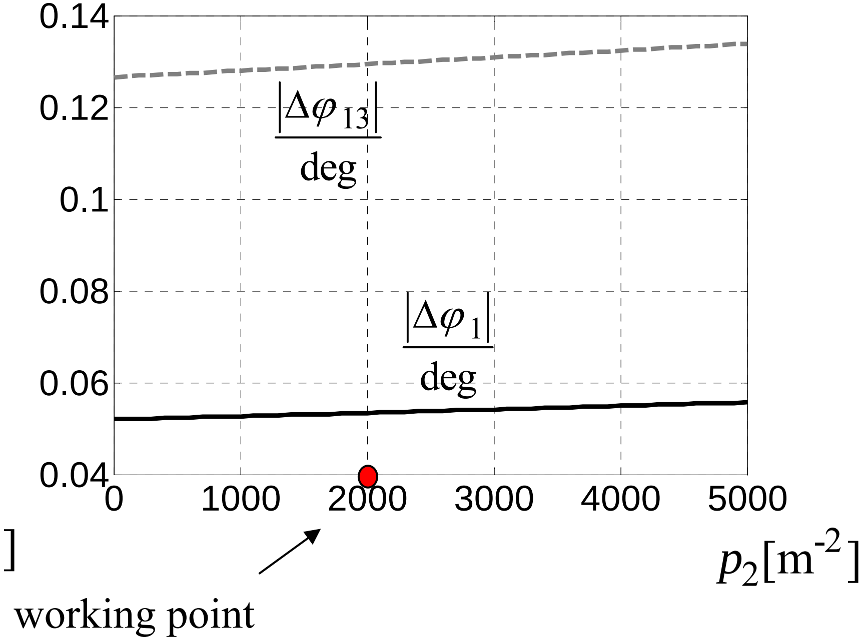
$\partial_s^2 C^{-1} = ?$

Working points (8 macroparameters)

Tolerances (10 % change of compression)

$$p_1 \equiv \partial_s C^{-1} = 0$$





$$\frac{V_{13}\partial C}{C^2 \partial V_{13}} = V_{13}\left(3Ak\sin(\varphi_{13}) - B\cos(\varphi_{13})\right)$$

$$\frac{\partial C}{C^2 \partial \varphi_{13}} = V_{13}\left(B\sin(\varphi_{13}) + 3Ak\cos(\varphi_{13})\right)$$

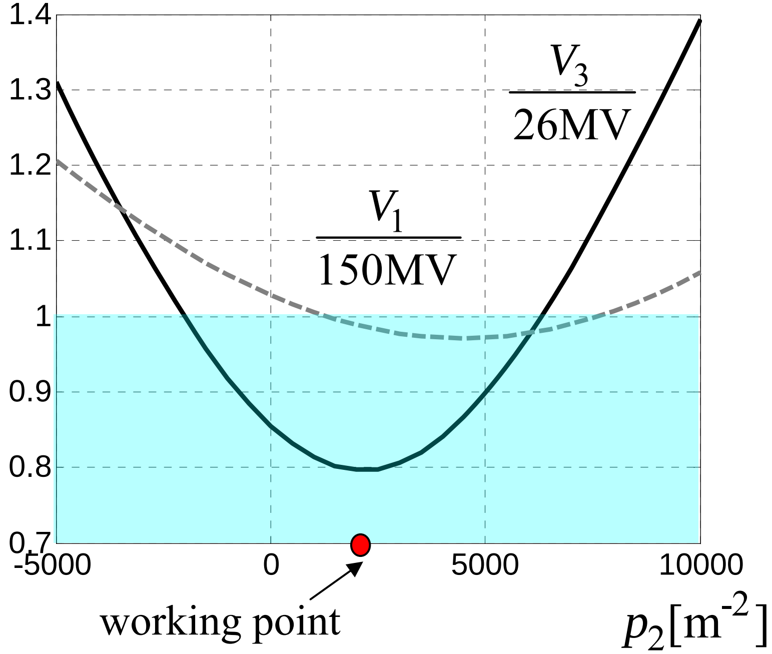
$$\frac{V_1\partial C}{C^2 \partial V_1} = V_1\left(Ak\sin(\varphi_1) - B\cos(\varphi_1)\right)$$

$$\frac{\partial C}{C^2 \partial \varphi_1} = V_1\left(B\sin(\varphi_1) + Ak\cos(\varphi_1)\right)$$

$$A = -\left[\frac{r_{561}}{E_1} + \frac{r_{562}}{E_2} + k\frac{r_{561}}{E_1}\frac{r_{562}}{E_2}V_2\sin(\varphi_2)\right]$$

$$B = \delta_1'\frac{r_{561}}{E_1} + \delta_2'\frac{r_{562}}{E_2} + \delta_1'\frac{r_{561}}{E_1}\frac{r_{562}}{E_2}kV_2\sin(\varphi_2)$$

Working points (8 macroparameters)



$$E_1 = 130\text{MeV}$$

$$\text{E}_2 = 450\text{MeV}$$

$$r_1 = 1.93\text{m}$$

$$r_2 = 6\text{m}$$

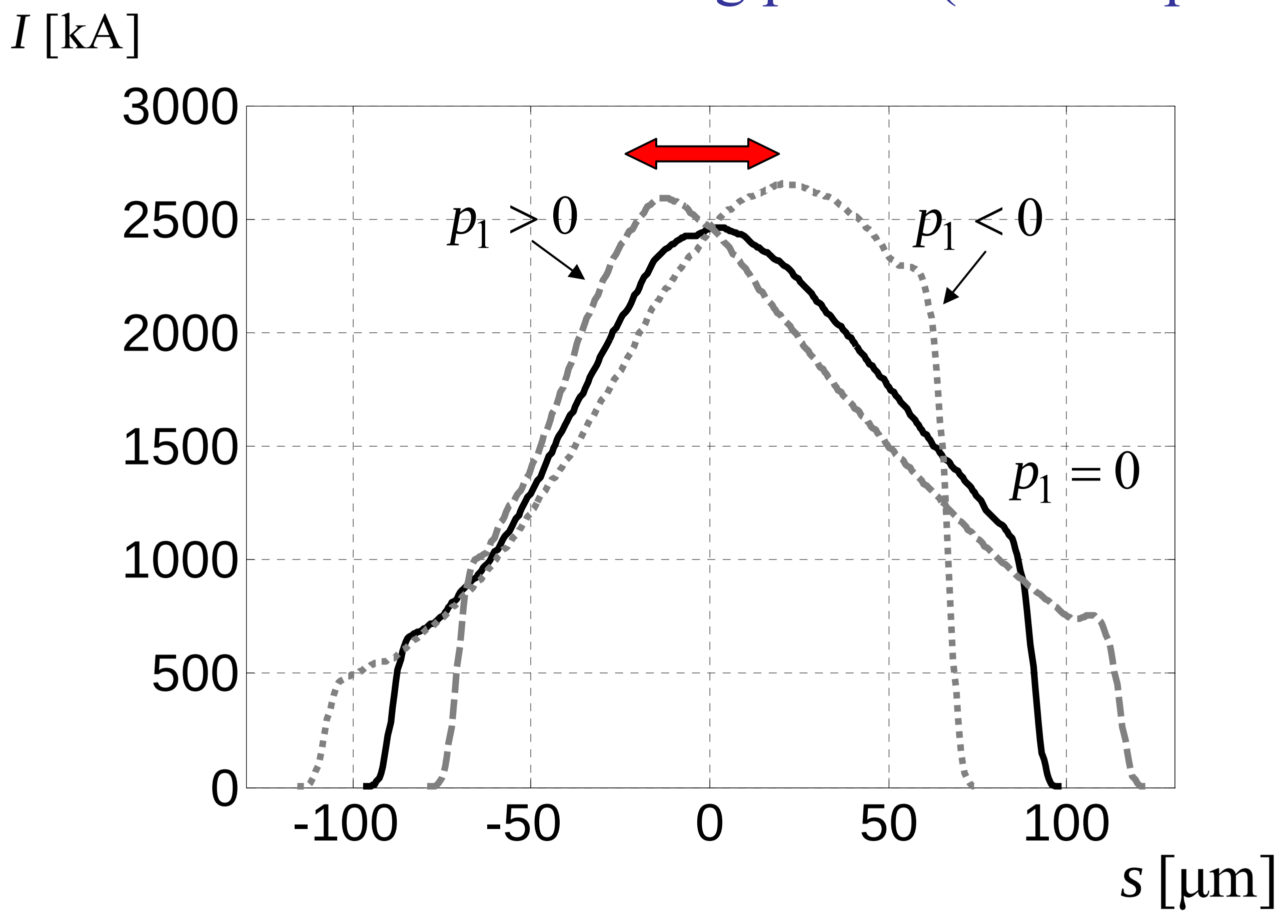
$$C = 48$$

$$C_1 = 2.84$$

$$\partial_s C^{-1} = ?$$

$$\partial_s^2 C^{-1} = 2000\text{m}^{-2}$$

Working points (8 macroparameters)



$E_1 = 130\text{MeV}$

$\text{E}_2 = 450\text{MeV}$

$\text{r}_1 = 1.93\text{m}$

$\text{C}=48$

$\text{C}_1 = 2.84$

$r_2 = 6\text{m}$

$p_2 = 2000\text{m}^{-2}$

$-1 \le \frac{p_1}{\text{m}^{-1}} \le 1$ - a free parameter to move the peak

Working points (8 macroparameters)

Charge Q, nC	Energy in BC2 E_1, [MeV]	Energy in BC3 E_2, [MeV]	Deflecting radius in BC2 r_1, [m]	Deflecting radius in BC3 r_2, [m]	Compression in BC2 C_1	Total compression C	First derivative p_1, [m^{-1}]	Second derivative p_2, [m^{-2}]
1	130	450	1.93	6	2.84	48	1	2e3
0.5				6.93	4.63	90	1	3.5e3
0.25				7.8	6.57	150	0.7	4e3
0.1				9.3	10.3	240	0	4e3
0.02				15.17	31.8 (12)	1000	-0.5	5e3

C_1 : scaling for different charges

$$x'' + k_x x = \frac{r_e}{ec\gamma^3}\frac{I}{\sigma_x(\sigma_x+\sigma_y)}x \quad \Rightarrow \quad \frac{\max[I_1(Q)]}{\sigma_r^2(Q)} \sim \frac{\max[I_1(Q)]}{\varepsilon(Q)} \sim \frac{\max[I_0(Q)]\,C_1(Q)}{\sqrt[2]{Q}} \sim const$$

we have used another scaling

$$\frac{\max[I_0(Q)]\,C_1(Q)}{\sqrt[4]{Q}} \sim const$$

Working points (6 equations => 6 RF parameters)

8 macroparameters define 6 equations

$$\begin{cases} E_2(0) = E_{20}, \quad E_1(0) = E_{10} \quad \dfrac{\partial s_1}{\partial s}(0) = C_1^{-1}, \\ \dfrac{\partial s_2}{\partial s}(0) = C^{-1}, \quad \dfrac{\partial^2 s_2}{\partial s^2}(0) = p_1, \quad \dfrac{\partial^3 s_2}{\partial s^3}(0) = p_2. \end{cases}$$

Analytical solution without self-fields*

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

nonlinear operator (defined analytically)

$$\mathbf{x}_0 = \begin{pmatrix} V_1 \\ \varphi_1 \\ V_{13} \\ \varphi_{13} \\ V_2 \\ \varphi_2 \end{pmatrix} \qquad \mathbf{f}_0 = \begin{pmatrix} E_{10} \\ E_{20} \\ C_1 \\ C \\ p_1 \\ p_2 \end{pmatrix}$$

*M.Dohlus and I.Zagorodnov,
A semi analytical modelling of two-stage
bunch compression with collective effects, (in preparation)

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)

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

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

$$\mathbf{f}_{n-1} = \mathbf{A}(\mathbf{x}_{n-1})$$

numerical tracking

$$\Delta\mathbf{f}_{n-1} = \mathbf{f}_0 - \mathbf{f}_{n-1}$$

residual in macroscopic parameters

$$\mathbf{g}_n = \mathbf{g}_{n-1} + \Delta\mathbf{f}_{n-1}$$

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

analytical correction of RF parameters

FLASH I
simulation methods (looking for working points)

1d analytical solution without collective effects
(8 macroparameters -> 6 RF settings)

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

1d tracking with space charge and wakes

~ **seconds** (1 cpu)

- accelerator: $E_1(s_1) = E_0(s_0) + V\cos(ks_0 + \varphi)$, $s_1 = s_0$
- compressor: $E_1(s_1) = E_0(s_0)$, $s_1(s_0) = s_0 + (r_{56}\delta + t_{566}\delta^2 + u_{5666}\delta^3)$

$\mathbf{A}_1(\mathbf{x}_1) = \mathbf{f}_0$ — ~ 5 iterations

quasi 3d tracking with all collective effects

~ **30 min** (1 cpu)

- accelerator: $E_1(s_1) = E_0(s_0) + V\cos(ks_0 + \varphi)$, $s_1 = s_0$, matrix transport for x & y
- **CSRtrack**

$\mathbf{x}_0 = \mathbf{x}_1$

$\mathbf{A}_2(\mathbf{x}_2) = \mathbf{f}_0$ — ~ 5 iterations

3d tracking with all collective effects

~ **10 h** (46 cpu-s)

- **Astra**
- **CSRtrack**

$\mathbf{A}(\mathbf{x}_2) \rightarrow \mathbf{f}$

$\mathbf{f} \approx \mathbf{f}_0$ — final result

Working points (6 equations => 6 RF parameters)

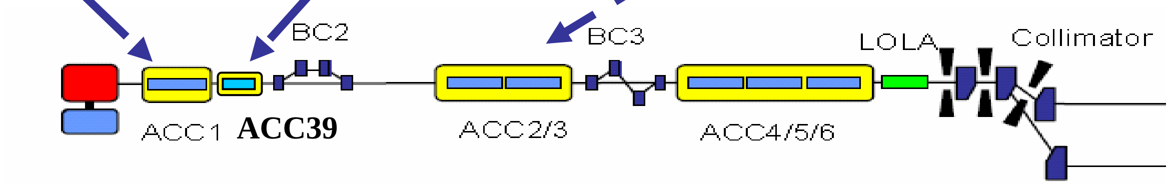
8 macroparameters define 6 equations

$$\begin{cases} E_2(0) = E_{20}, \quad E_1(0) = E_{10} \quad \dfrac{\partial s_1}{\partial s}(0) = C_1^{-1}, \\ \dfrac{\partial s_2}{\partial s}(0) = C^{-1}, \quad \dfrac{\partial^2 s_2}{\partial s^2}(0) = p_1, \quad \dfrac{\partial^3 s_2}{\partial s^3}(0) = p_2. \end{cases}$$

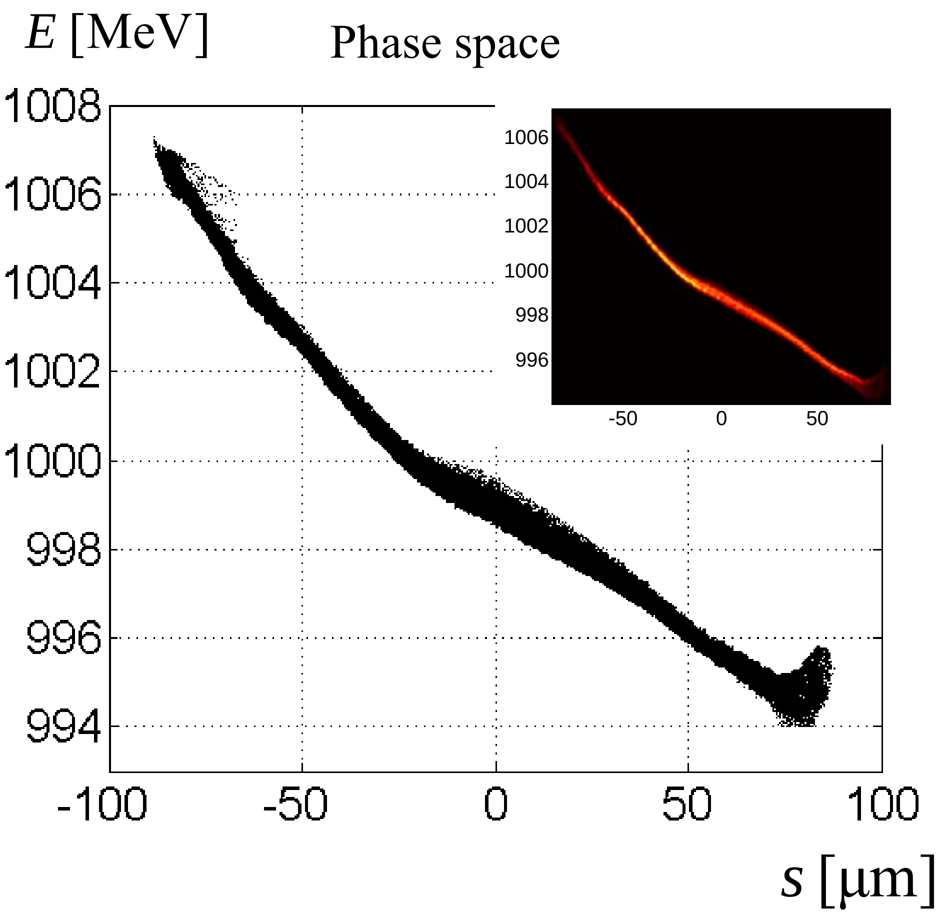
Analytical solution without self-fields + iterative procedure with them

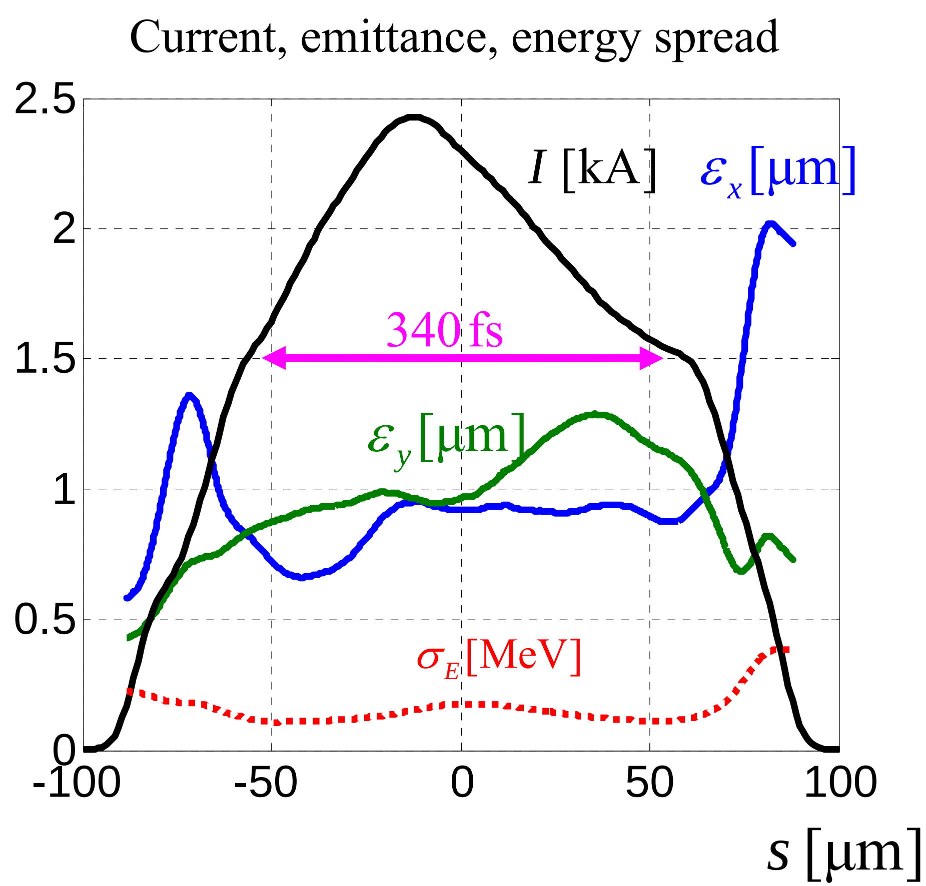
RF settings in accelerating modules

Charge, nC	V_1, [MV]	φ_1, [deg]	V_{39}, [MV]	φ_{39}, [deg]	V_2, [MV]	φ_2, [deg]
1	144	-4.66	22.6	145	350	23.4
0.5	143.7	4.042	19.65	158.4	351	23.65
0.25	143.36	2.493	20.81	153.9	352.6	23.96
0.1	144.8	-6.31	25.6	137.5	356.5	25.62
0.02	144.9	-3.894	25.58	141.65	339.8	19.385



Q=1 nC

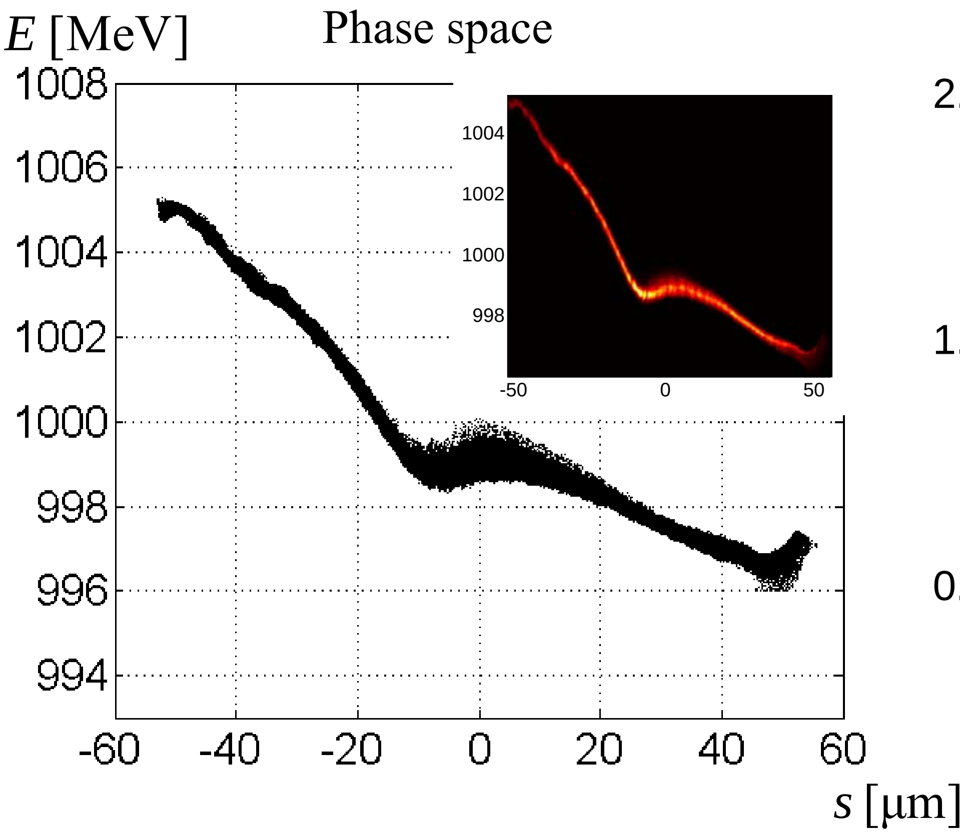


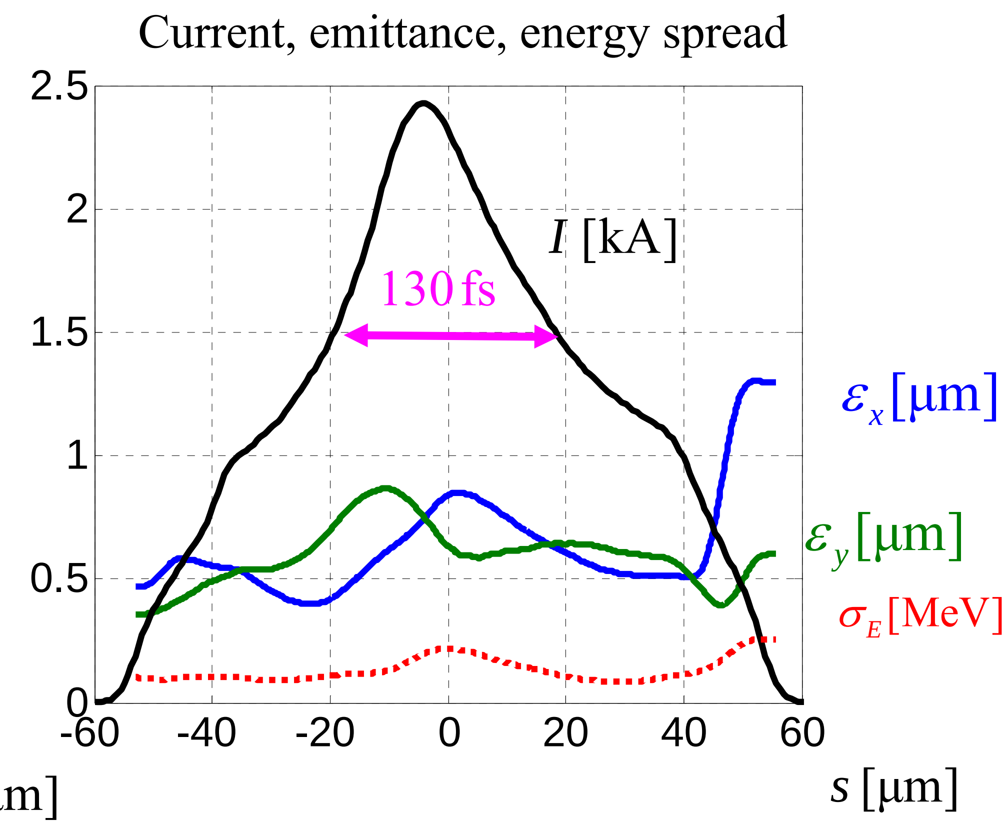


$$\varepsilon_x^{proj} = 3\ [\mu m]$$

$$\varepsilon_y^{proj} = 1.4\ [\mu m]$$

Q=0.5 nC

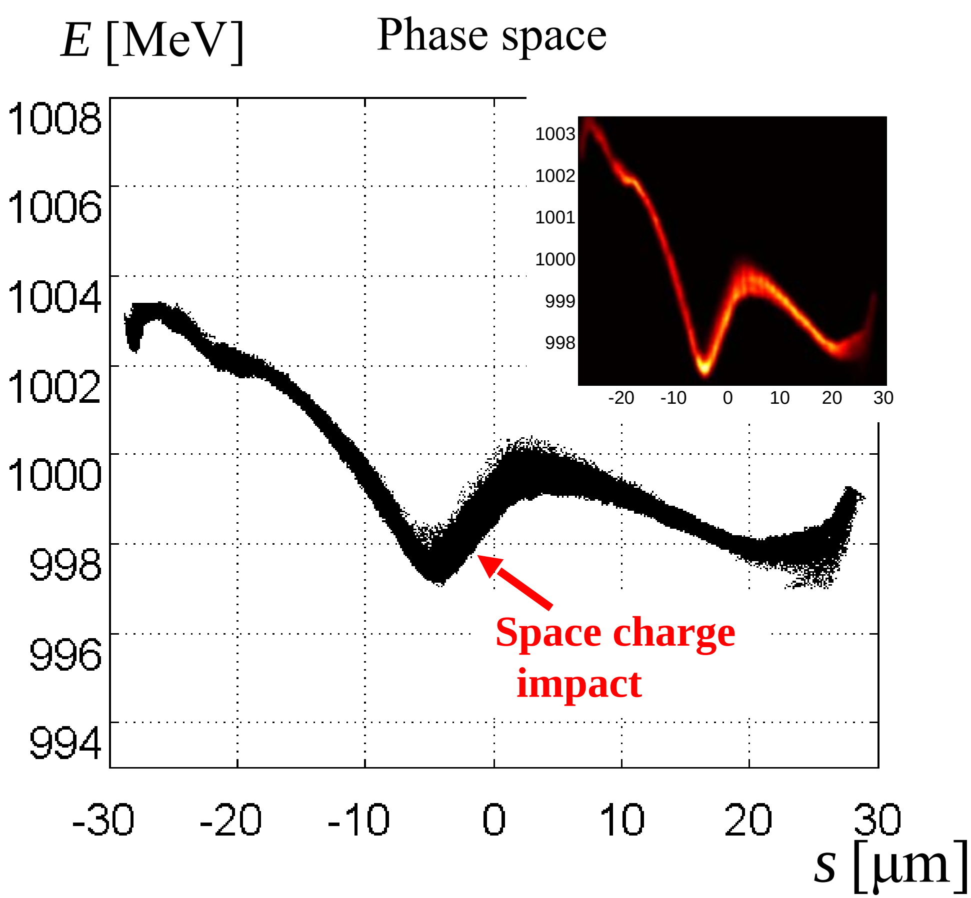


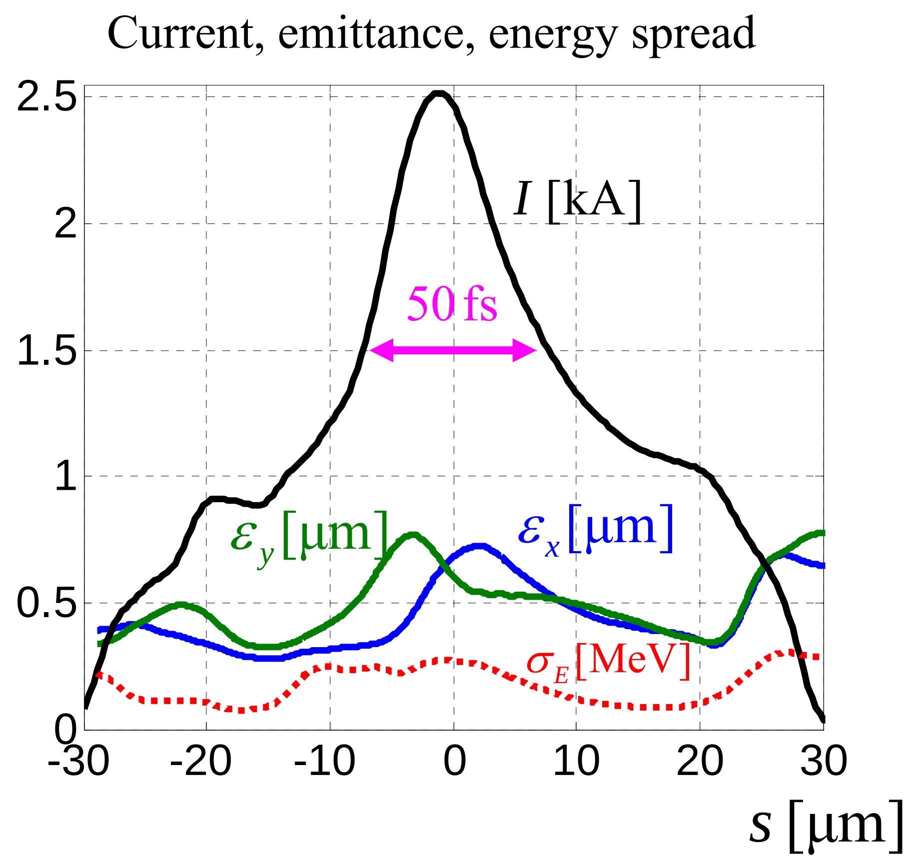


$$\varepsilon_x^{proj} = 2.5\,[\mu\mathrm{m}]$$

$$\varepsilon_y^{proj} = 0.84\,[\mu\mathrm{m}]$$

Q=0.25 nC

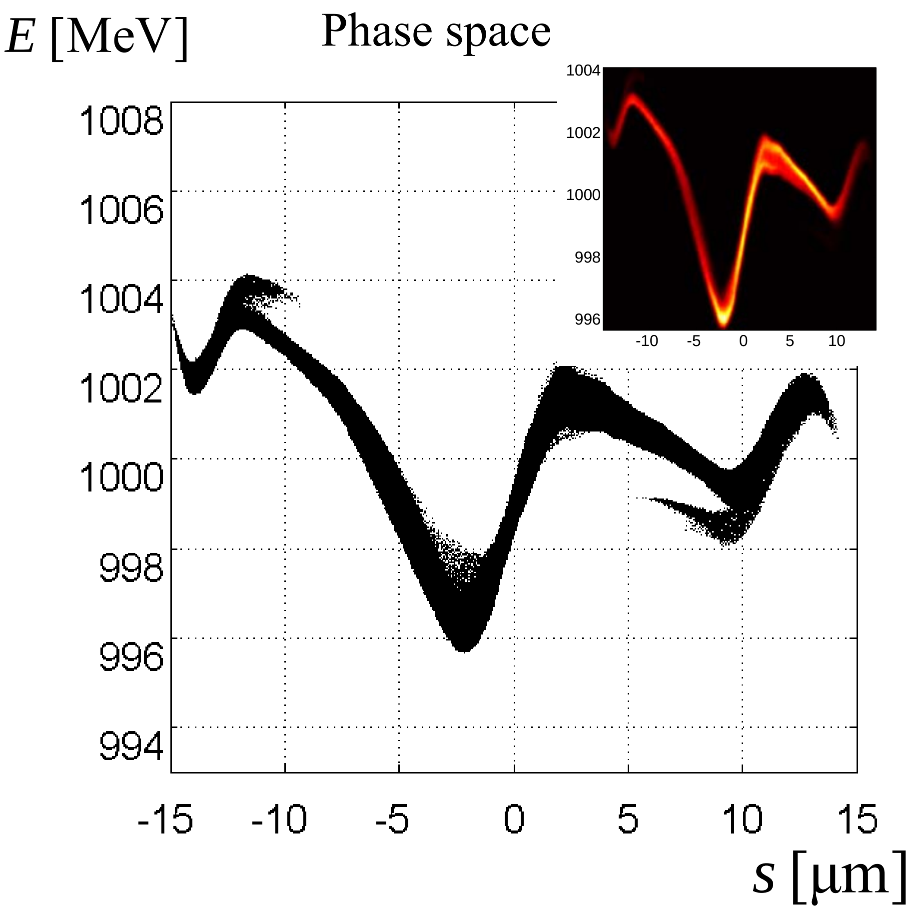


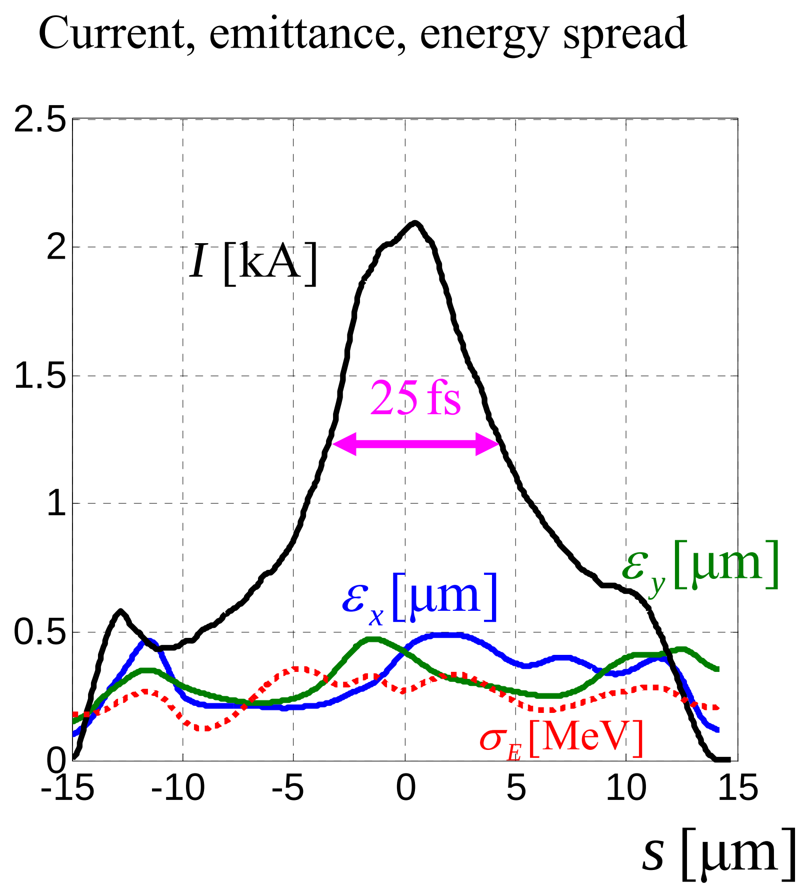


$$\varepsilon_x^{proj} = 1.14\ [\mu m]$$

$$\varepsilon_y^{proj} = 0.74\ [\mu m]$$

Q=0.1 nC

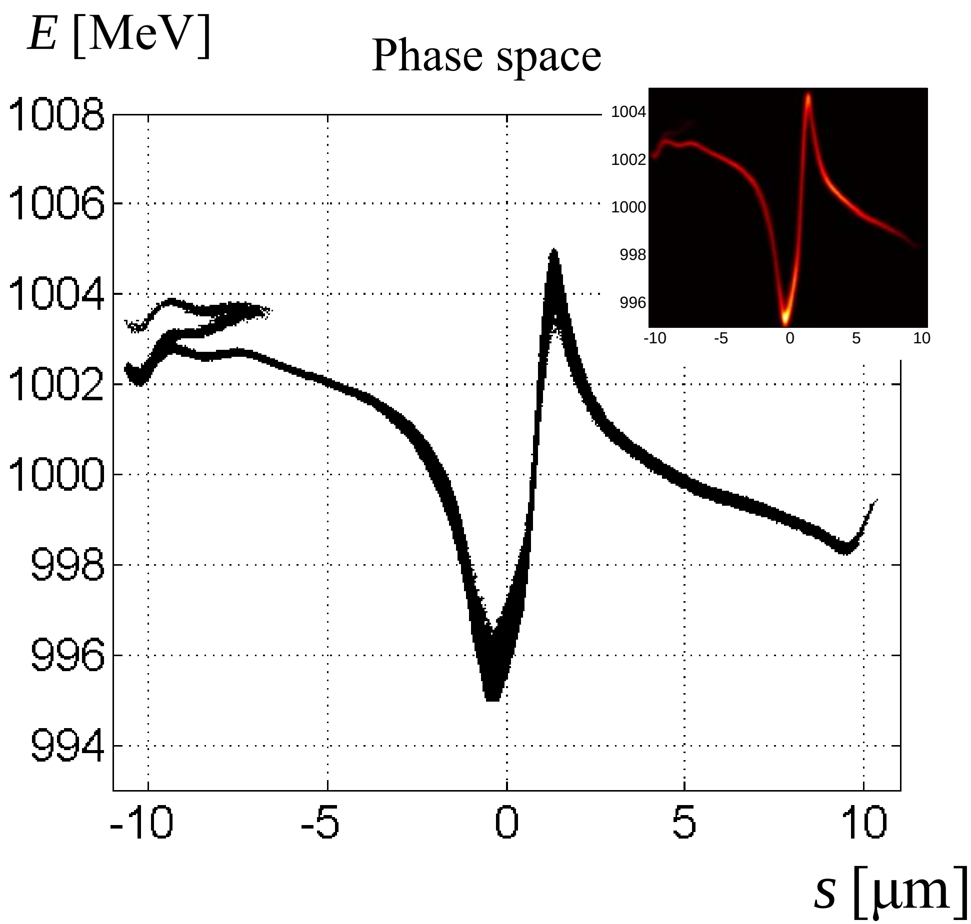


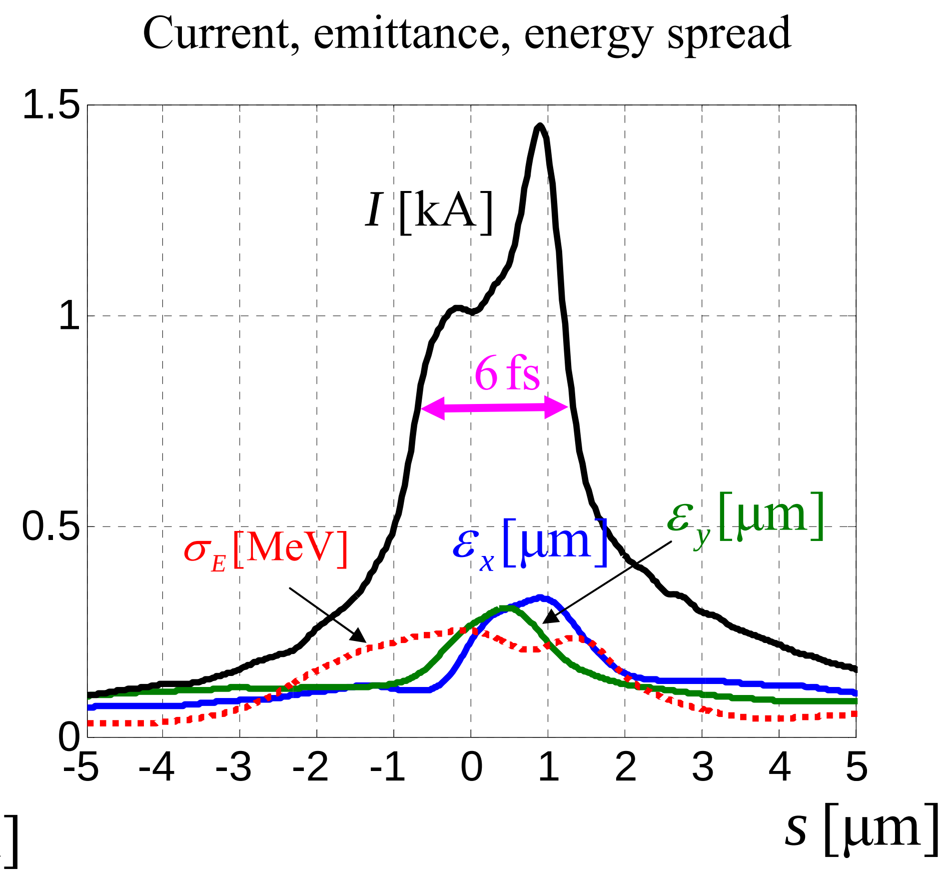


$$\varepsilon_x^{proj} = 2\ [\mu m]$$

$$\varepsilon_y^{proj} = 0.6\ [\mu m]$$

Q=0.02 nC

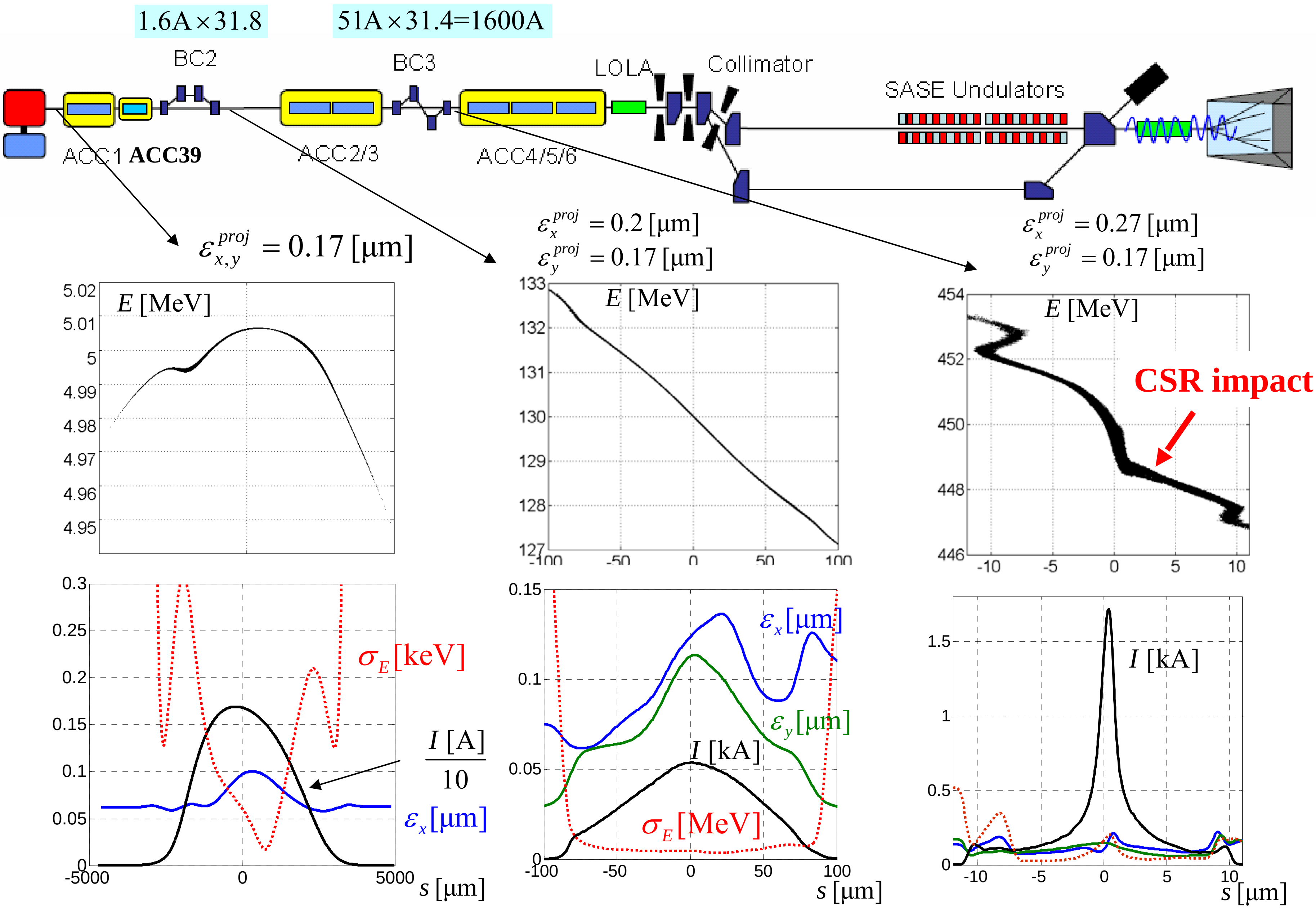




$$\varepsilon_x^{proj} = 0.48\,[\mu m]$$

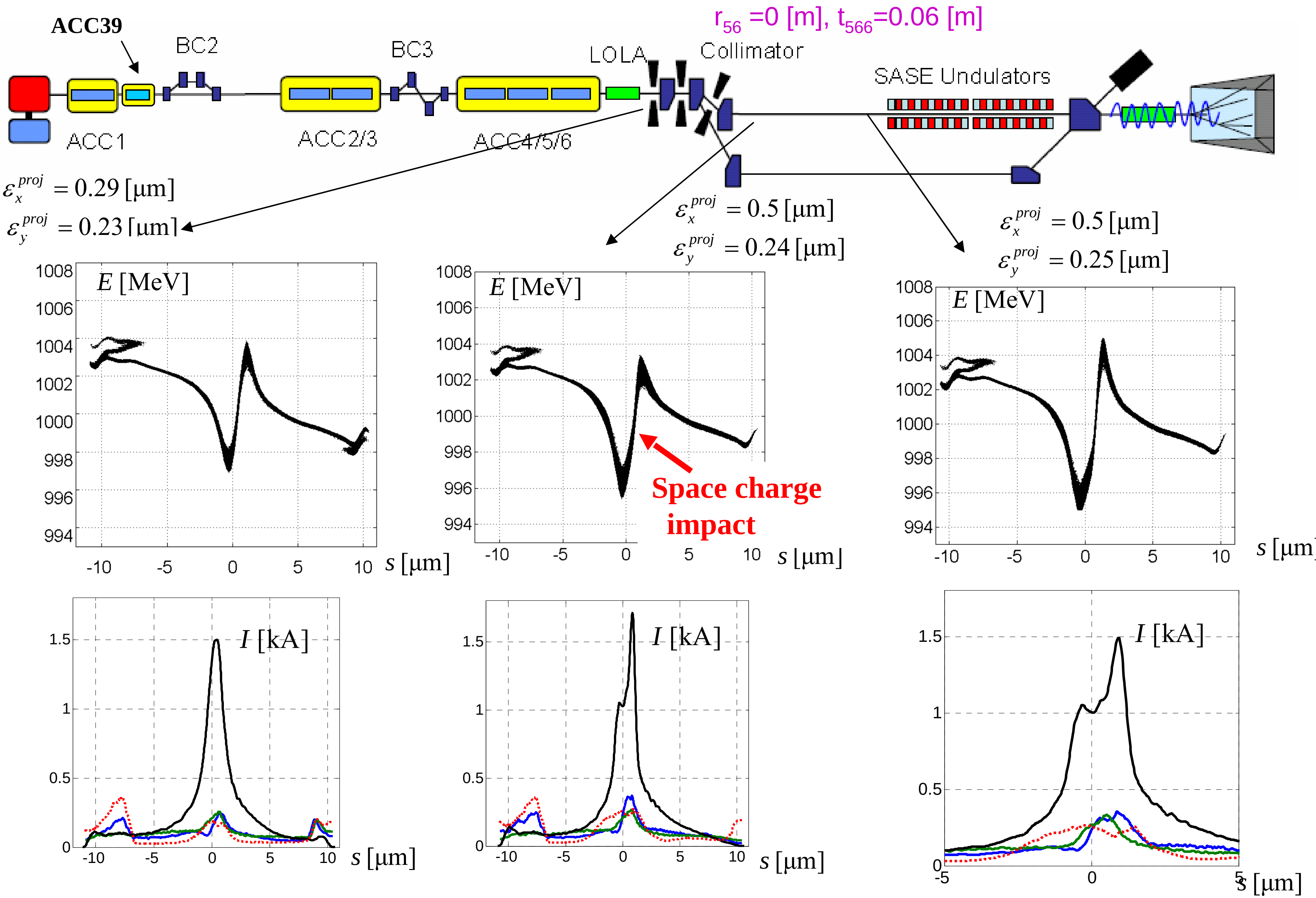
$$\varepsilon_y^{proj} = 0.25\,[\mu m]$$

Q=0.02 nC



1.6A × 31.8
51A × 31.4=1600A
BC2
BC3
LOLA
Collimator
SASE Undulators
ACC1 ACC39
ACC2/3
ACC4/5/6
$\varepsilon_{x,y}^{proj} = 0.17$ [μm]
$\varepsilon_{x}^{proj} = 0.2$ [μm]
$\varepsilon_{y}^{proj} = 0.17$ [μm]
$\varepsilon_{x}^{proj} = 0.27$ [μm]
$\varepsilon_{y}^{proj} = 0.17$ [μm]
E [MeV]
CSR impact
σ_E [keV]
I [A] / 10
ε_x [μm]
ε_y [μm]
I [kA]
σ_E [MeV]
s [μm]

Q=0.02 nC


ACC39
BC2
BC3
LOLA
Collimator
r_{56} =0 [m], t_{566}=0.06 [m]
SASE Undulators
ACC1
ACC2/3
ACC4/5/6
$\varepsilon_x^{proj} = 0.29$ [μm]
$\varepsilon_y^{proj} = 0.23$ [μm]
$\varepsilon_x^{proj} = 0.5$ [μm]
$\varepsilon_y^{proj} = 0.24$ [μm]
$\varepsilon_x^{proj} = 0.5$ [μm]
$\varepsilon_y^{proj} = 0.25$ [μm]
E [MeV]
Space charge impact
s [μm]
I [kA]

Tolerances (analytically) **without self fields** (10 % change of compression)

Q, nC			1	0.5	0.25	0.1	0.02
ACC1	$\lvert\Delta V\rvert/V$	Scaling	0.34	0.013	0.006	0.0014	0.0002
	$\lvert\Delta\varphi\rvert$, degree		**0.05**	**0.024**	**0.013**	**0.008**	**0.0016**
ACC39	$\lvert\Delta V\rvert/V$	**~O(C^{-1})**	0.05	0.007	0.0035	0.0011	0.0002
	$\lvert\Delta\varphi\rvert$, degree		0.13	0.061	0.033	0.019	0.004
ACC2/3	$\lvert\Delta V\rvert/V$		0.09	0.023	0.014	0.01	0.0054
	$\lvert\Delta\varphi\rvert$, degree	~O(C_2^{-1})	0.19	0.21	0.22	0.28	0.36

Tolerances (from tracking) **with self fields** (10 % change of compression)

Q, nC		1	0.5	0.25	0.1	0.02
ACC1	$\lvert\Delta V\rvert/V$	0.0041	0.0035	0.0015	0.0004	0.0001
	$\lvert\Delta\varphi\rvert$, degree	**0.063**	**0.026**	**0.015**	**0.009**	**0.0019**
ACC39	$\lvert\Delta V\rvert/V$	0.0037	0.0027	0.0011	0.0004	0.0001
	$\lvert\Delta\varphi\rvert$, degree	0.16	0.07	0.04	0.024	0.005
ACC2/3	$\lvert\Delta V\rvert/V$	0.24	0.026	0.015	0.01	0.0054
	$\lvert\Delta\varphi\rvert$, degree	0.18	0.2	0.2	0.26	0.35

FLASH
parameters

How to provide (1) a well conditioned electron beam and (2) what are the properties of the radiation?

(1) Self consistent beam dynamics simulations.

We are able to provide the well conditioned electron beam for different charges.

But RF tolerances for small charges are tough.

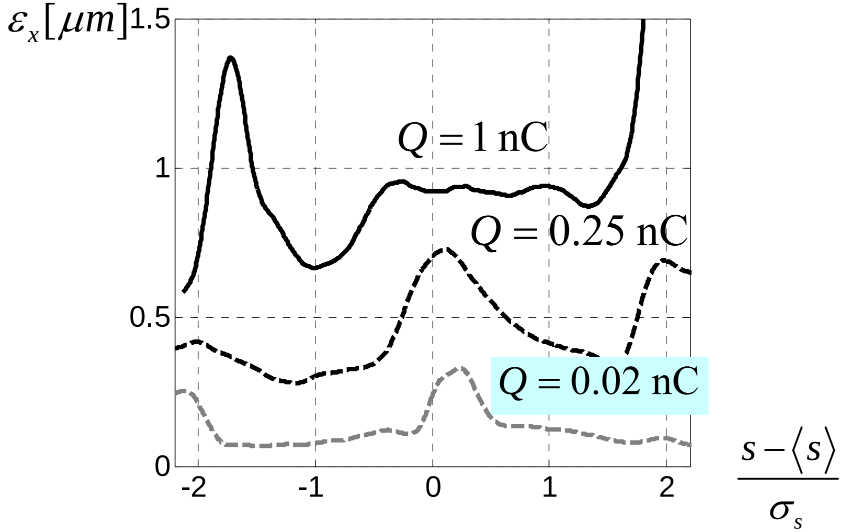
(2) FEL simulations (next slides).

Slice parameters for SASE simulations

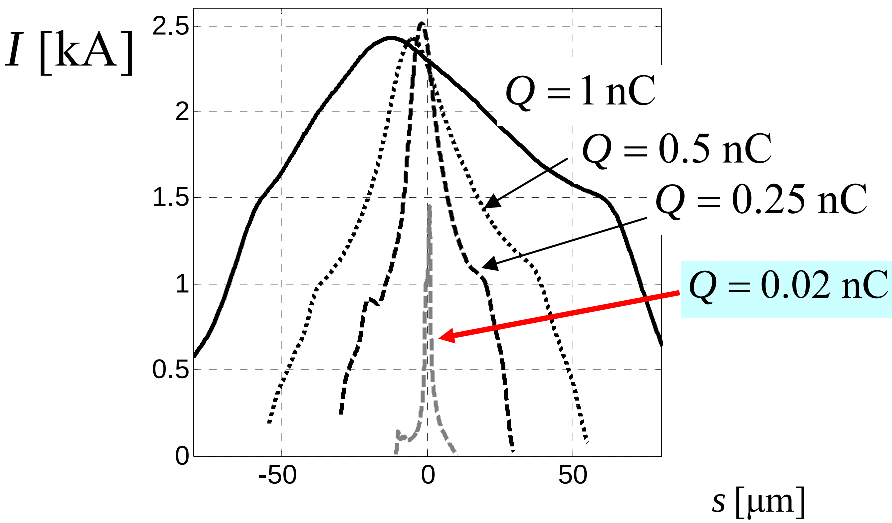
Slice parameters are extracted from S2E simulations for SASE simulations

$$\gamma \quad \Delta\gamma \quad \varepsilon_x \quad \varepsilon_y \quad \beta_x \quad \beta_y \quad \langle x \rangle \quad \langle y \rangle \quad \langle x' \rangle \quad \langle y' \rangle \quad \alpha_x \quad \alpha_y \quad I$$

slice emittance

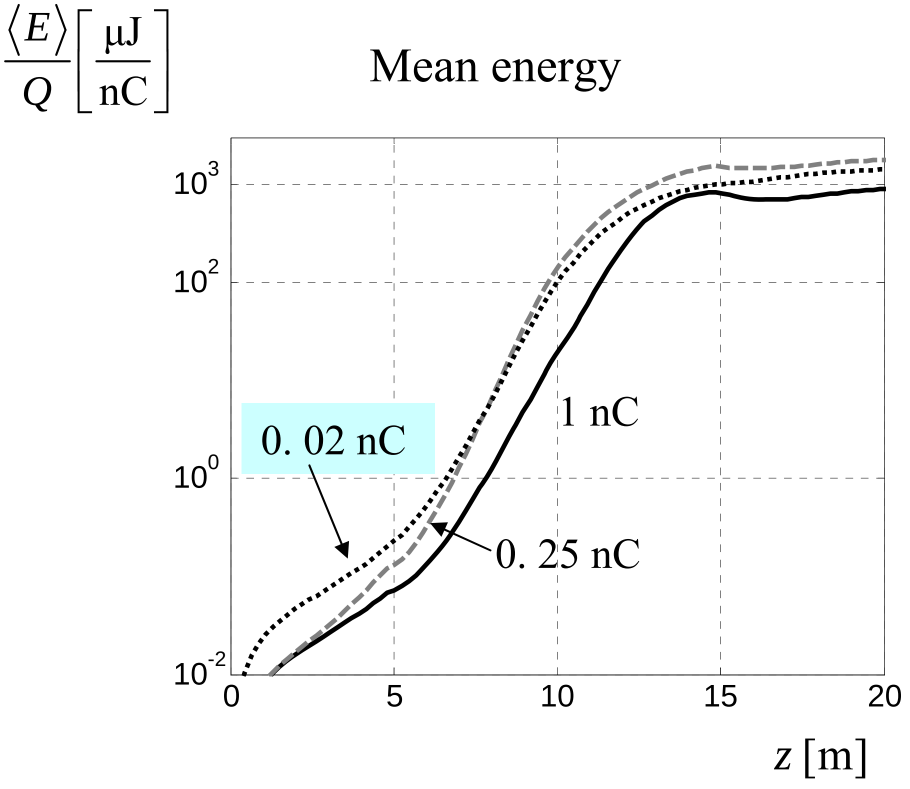


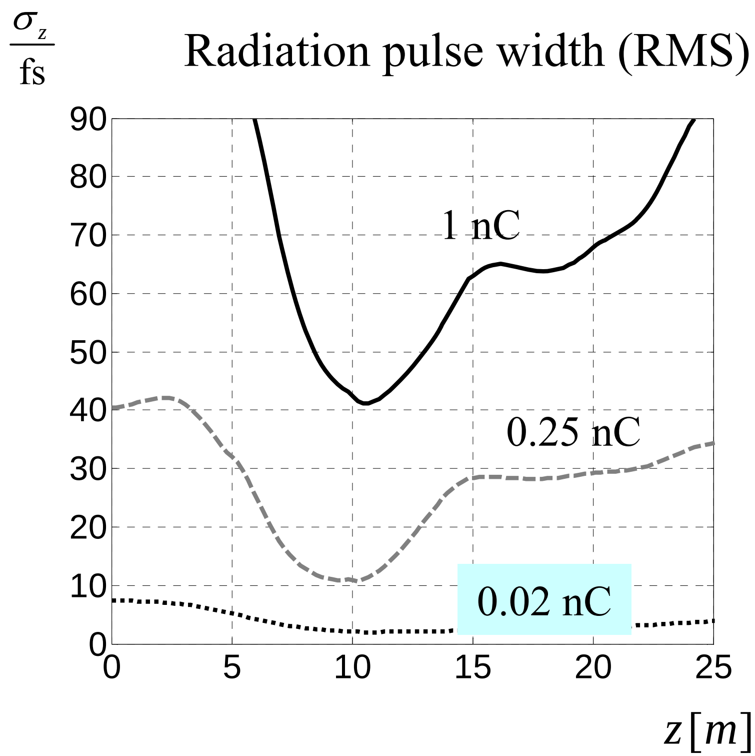
current



Charge Q, nC	1	0.25	0.02
Longitudinal electron beam size σ_s, μm	42	13	3.6
Transverse electron beam size σ_r, μm	80	68	36

Radiation energy statistics (200-500 runs)



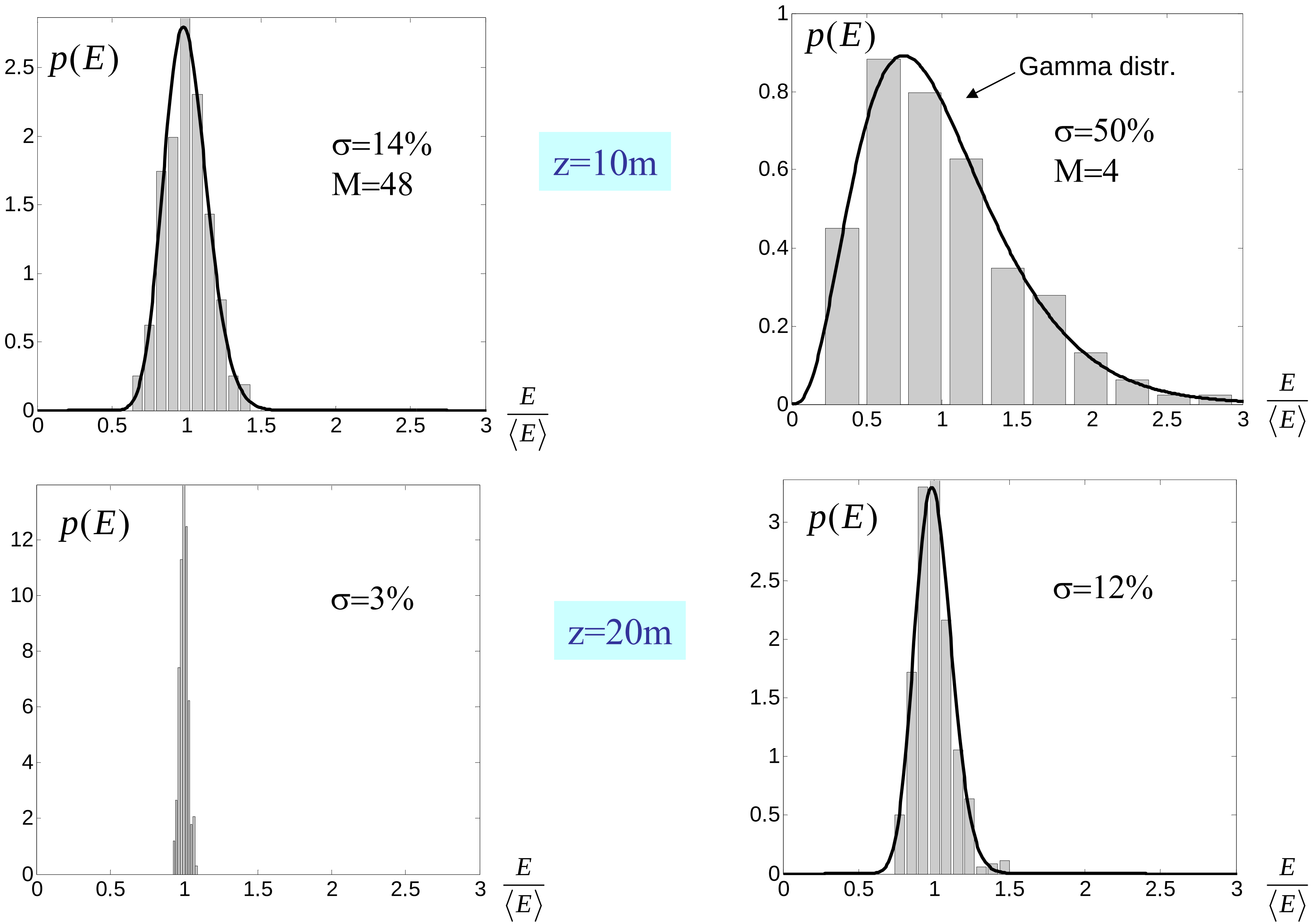


Charge, nC	1	0.5	0.25	0.1	0.02
Mean radiation energy, μJ	1000-1400	700	500	200	30
Pulse radiation width (FWHM), fs	**70**	**30**	**17**	**7**	**2**

Radiation energy statistics

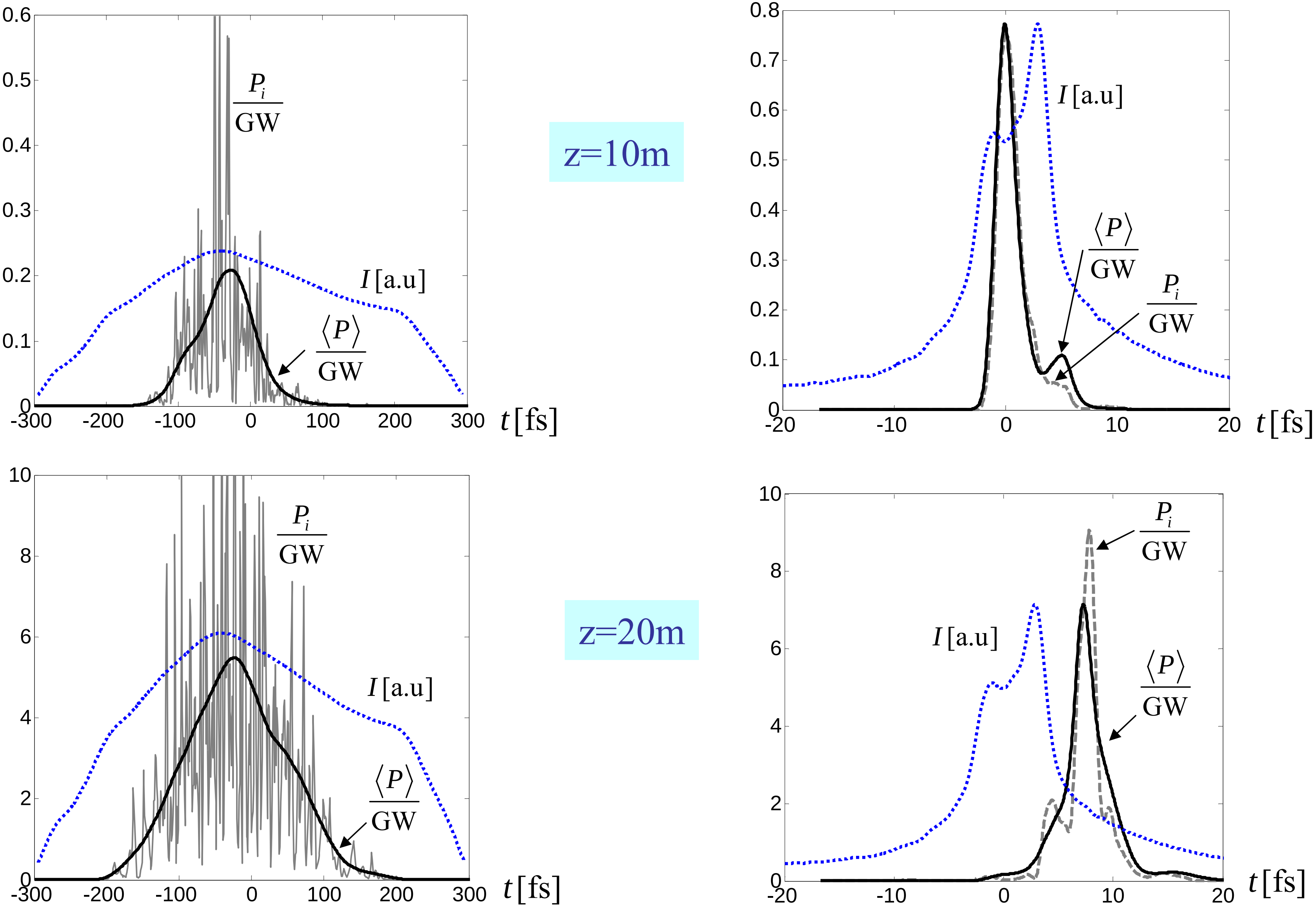
Q=1 nC

Q=0.02 nC



Temporal structure

Q= 1 nC | Q=0.02 nC



Summary

	with harmonic module					without*
Bunch charge, nC	1	0.5	0.25	0.1	0.02	0.5-1
Wavelength, nm	6.5					6
Beam energy, MeV	1000					1000
Peak current, kA	**2.5**			**2.1**	**1-1.5**	1.3-2.2
Slice emmitance,mm-mrad	**1-1.3**	**0.7-0.9**	**0.5-0.7**	**0.4-0.5**	**0.3-0.4**	1.5-3.5
Slice energy spread, MeV	0.1-0.2	0.1-0.2	0.25	0.2-0.4	0.25	0.3
Saturation length, m	**13**	**12**	**11**	**10**	**11**	22-32
Energy in the rad. pulse, μJ	1000-1400	700	500	200	30	50-150
Radiation pulse duration FWHM, fs	**70**	**30**	**17**	**7**	**2**	15-50
Averaged peak power, GW	5-7					2-4
Spectrum width, %	0.4-0.6			0.8-1		0.4-0.6
Coherence time, fs	4-5			-	-	-

*) E.L.Saldin at al, Expected properties of the radiation from VUV-FEL at DESY, TESLA FEL 2004-06, 2004.

FLASH
Simulation results

(1) Self consistent beam dynamics simulations

We are able to provide the well conditioned electron beam for different charges.
But RF tolerances for small charges are tough.

(2) FEL simulations

The charge tuning (20-1000 pC) in SASE mode allows to tune

- the radiation pulse energy (30-1400 mJ)
- the pulse width (FWHM 3-70 fs).