Study of ACC1 voltage amplitude changing impact on SASE at FLASH

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MPY, DESY

Contents

Introduction

In February this year, a phenomenon was found during the SASE FEL experiment: When the voltage amplitude of ACC1 is adjusted from about 161MV to 166MV, SASE FEL can’t be tuned only by adjusting the RF parameters of the accelerating modules.

Choice of the RF parameters values of the accelerating modules

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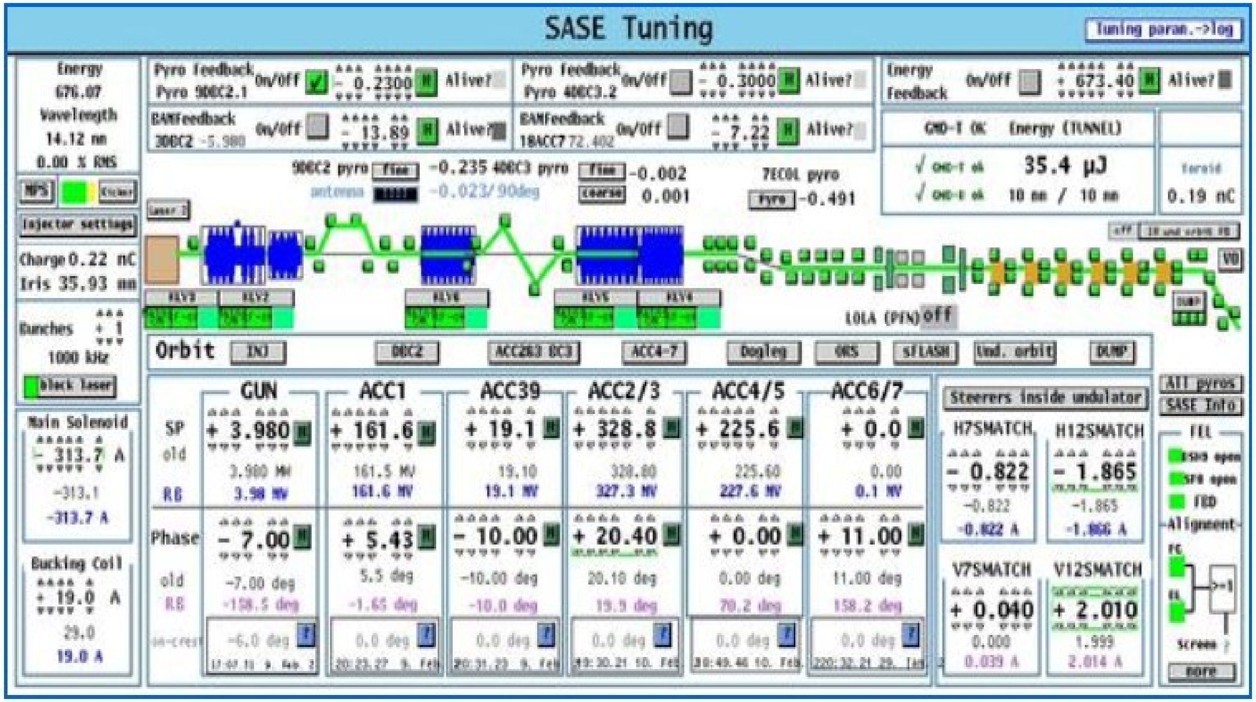
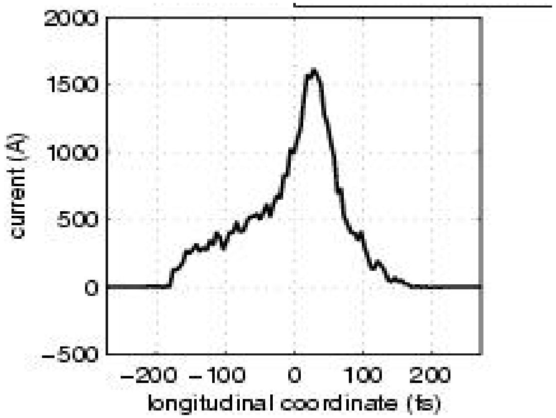




Q=0.22nC

I_{BC2}=72.7A, I_{BC3}=56.09A

Restrictions

(1) In case1, RF parameters values should be closed to the setting points in the logbook.

(2) In case2, the voltage amplitude of ACC1 is about 166.6MV.

(3) In both of the two cases,

E=146MeV after ACC39

E=450MeV after ACC3

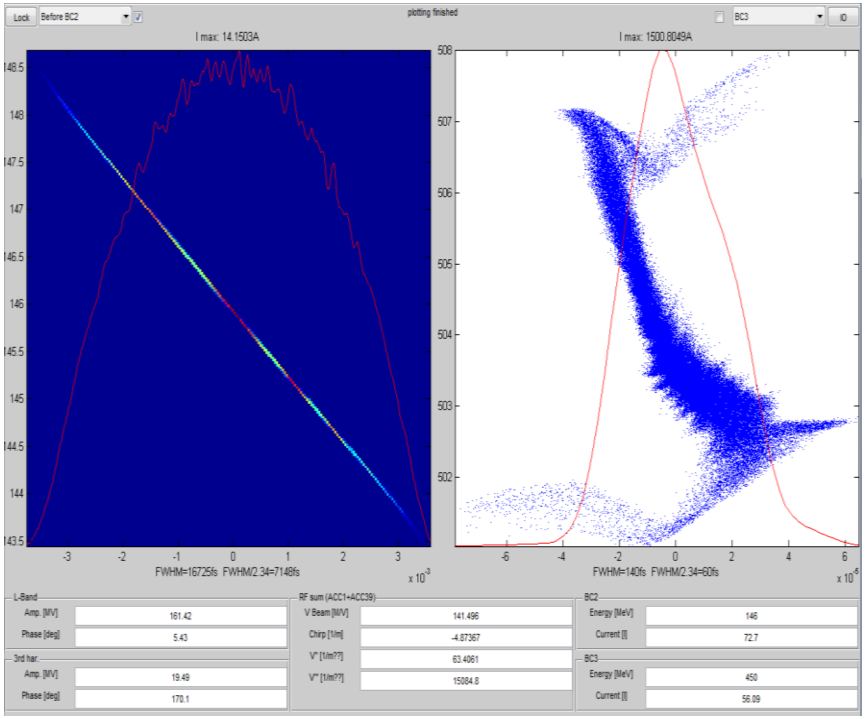
Case1

V_1=161.42MV

$\varphi_1 = 5.43°$

$V_{39} = 19.49\text{MV}$

$\varphi_3 = 170.1°$



$$\begin{pmatrix} \varphi_1 \\ V_{39} \\ \varphi_3 \end{pmatrix} = M \begin{pmatrix} V(0) \\ V'(0) \\ V''(0) \end{pmatrix}$$

$$V(0) = V_1 \mathrm{Cos}(\varphi_1) + V_{39} \mathrm{Cos}(\varphi_3)$$

Case1

V_1=161.42MV
$\varphi_1 = 5.430°$
$V_{39} = 19.49\mathrm{MV}$
$\varphi_3 = 170.1°$

→

$V(0) = 141.5\mathrm{MV}$
$V'(0) = -690\mathrm{MV/m}$
$V''(0)$=8984MV/m^2

→

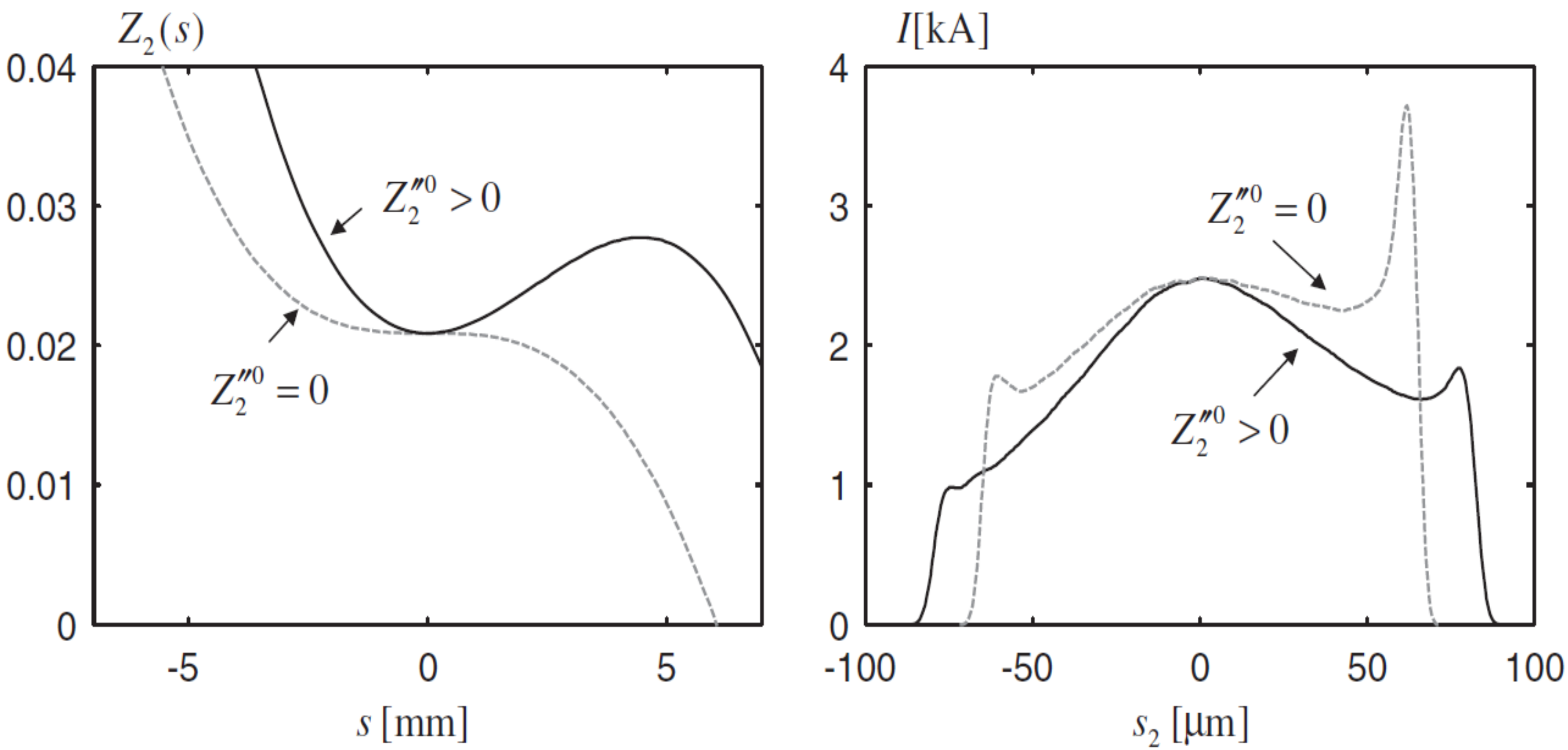
Case2 (V_1=166.6MV)

$\varphi_1 = 15.26°$
$V_{39} = 20.188\mathrm{MV}$
$\varphi_3 = 197.79°$

Difference between Case1 and Case2

	Case1	Case2
$\mathbf{V'''(0)}$ [MV/m^3]	2.13665×10^6	-2.48147×10^6

Impact of $V'''(0)$ on the current profile



If the parameter $V'''(0)$is large enough, we will have a stronger compression at the middle of the bunch and a weaker compression in the head and the tail.

* Igor Zagorodnov, Martin Dohlus, Semianalytical modeling of multistage bunch compression with collective effects, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 14, 014403 (2011)

Estimation of the Bmag at the end of ACC1 between the two cases

SASE FEL

- **One dimensional model**

$$P_{beam}[TW] = E_0[GeV] I[kA]$$

$$\sigma_x = \sqrt{\beta \varepsilon_n / \gamma_0}$$

Beta function

Beam emittance

Pierce parameter $$\rho = \left[\left(\frac{I}{I_A}\right) \left(\frac{\lambda_w A_w}{2\pi\sigma_x}\right)^2 \left(\frac{1}{2\gamma_0}\right)^3 \right]^{1/3}$$

Beam current

$$P_n \approx \rho^2 c E_0 / \lambda$$

$$L_g = \lambda_w / 4\pi\sqrt{3}\rho$$

$$\boldsymbol{P_{sat} \approx \rho P_{beam}\,, \qquad L_{sat} = L_g Ln\left(\frac{P_{sat}}{\alpha P_n}\right)}$$

- **Formula obtained empirically by fitting simulation results**

$$\boldsymbol{P_{sat} \approx 1.6\rho \left(\frac{L_{1d}}{L_g}\right)^2 P_{beam}}$$

Energy spread

Universal scaling function $$\frac{L_{1d}}{L_g} = F(\eta_d, \eta_\varepsilon, \eta_\gamma)$$

Where $$\eta_d = \frac{L_{1d}}{4\pi\sigma_x^2/\lambda},\ \eta_\varepsilon = \left(\frac{L_{1d}}{\beta}\right)\left(\frac{4\pi\varepsilon}{\lambda}\right),\ \eta_\gamma = 4\pi\left(\frac{L_{1d}}{\lambda_w}\right)\left(\frac{\sigma_e}{E_0}\right)$$

Transfer matrix of the standing wave cavity*

$$M_{cavity} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}$$

$$= \begin{pmatrix} \mathrm{Cos}(\alpha) - \sqrt{2}\,\mathrm{Cos}(\Delta\emptyset)\mathrm{Sin}(\alpha) & \sqrt{8}\,\frac{\gamma_i}{\gamma'}\mathrm{Cos}(\Delta\emptyset)\mathrm{Sin}(\alpha) \\ -\frac{\gamma'}{\gamma_f}\left[\frac{\mathrm{Cos}(\Delta\emptyset)}{\sqrt{2}} + \frac{1}{\sqrt{8}\mathrm{Cos}(\Delta\emptyset)}\right]\mathrm{Sin}(\alpha) & \frac{\gamma_i}{\gamma_f}\left[\mathrm{Cos}(\alpha) + \sqrt{2}\mathrm{Cos}(\Delta\emptyset)\mathrm{Sin}(\alpha)\right] \end{pmatrix}$$

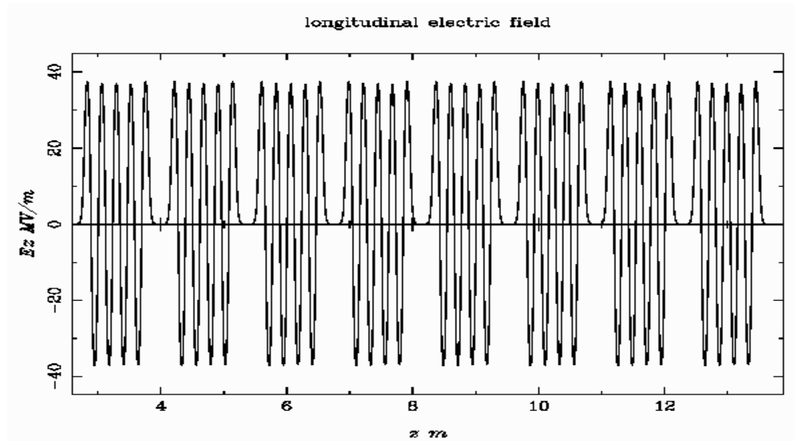
$$\alpha = \frac{\mathrm{Ln}\left(\frac{\gamma_f}{\gamma_i}\right)}{\sqrt{8}Cos(\Delta\emptyset)}$$

$\gamma' = (\gamma_f - \gamma_i)/L_{Cavity}$

$\Delta\emptyset$: Accelerating phase shift of the cavity

* J. Rosenzweig, Transverse particle motion in radio-frequency linear accelerators, PHYSICAL REVIEW E, VOLUME 49, NUMBER 2, 1994

Longitudinal electric field distribution in ACC1



First Cavity of ACC1

	L_{Cavity} [m]	$\Delta\emptyset$ [°]	γ_i	γ_f	γ' [1/m]	α	m_{21} [1/m]
Case1	1.3757	5.43	9.80626	49.1154	28.5739	0.572196	−0.333628
Case2	1.3757	15.26	9.80626	49.1228	28.5793	0.590501	−0.339688

m_{21} for each cavity of ACC1

m_{21} for ACC1's cavity	#1	#2	#3	#4	#5	#6	#7	#8
Case1	**-0.33363**	-0.07095	-0.03086	-0.01724	-0.01100	-0.00762	-0.00560	-0.00428
Case2	**-0.33969**	-0.07246	-0.03152	-0.01761	-0.01124	-0.00779	-0.00572	-0.00437

Stronger focusing in the first cavity

Thin lens approximation of the first cavity

A thin lens model of the first cavity of ACC1

$$\mathrm{M}_{\mathrm{cavity}} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -Kl & 1 \end{pmatrix}$$

$$K_1 l = 0.333628\ 1/m$$

$$K_2 l = 0.339688\ 1/\mathrm{m}$$

$$B_{mag} = \frac{1}{2}\left[\frac{\beta_2}{\beta_1} + \frac{\beta_1}{\beta_2} + \left(\alpha_2\sqrt{\frac{\beta_1}{\beta_2}} - \alpha_1\sqrt{\frac{\beta_2}{\beta_1}}\right)^2\right]$$

$$= \frac{1}{2}\left[2 + {\alpha_1}^2 + {\alpha_2}^2 - 2\alpha_1\alpha_2\right]$$

$\beta_0 \approx 1.0m$ in the first cavity of ACC1

$$B_{mag\approx}\frac{1}{2}\left[2 + \left(\frac{\gamma_f}{\gamma_i}\right)^2 (\Delta K)^2 l^2 {\beta_0}^2\right] \approx 1.00046$$

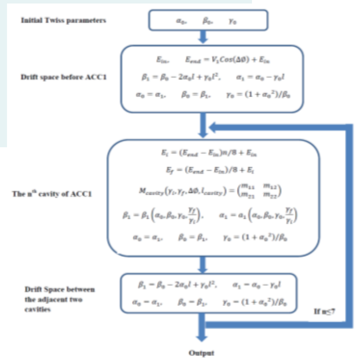
Bmag calculation by using transfer matrix for ACC1 section

- Initial twiss parameters before ACC1 and the information of the drift space and the cavities come from Elegant lattice file*.
- Transfer matrix of standing wave cavity is used to simulate each cavity of ACC1.

Twiss parameters before ACC1

$$\beta_0 = 0.7148m$$
$$\alpha_0 = -1.3166$$

	V_1 (MV)	$\Delta\varphi_1$ (°)	β_1 (m)	α_1	B_{mag}
Case1	161.42	5.43	15.7619	-0.7297	**1.00172**
Case2	166.6	15.26	15.1848	-0.7475	

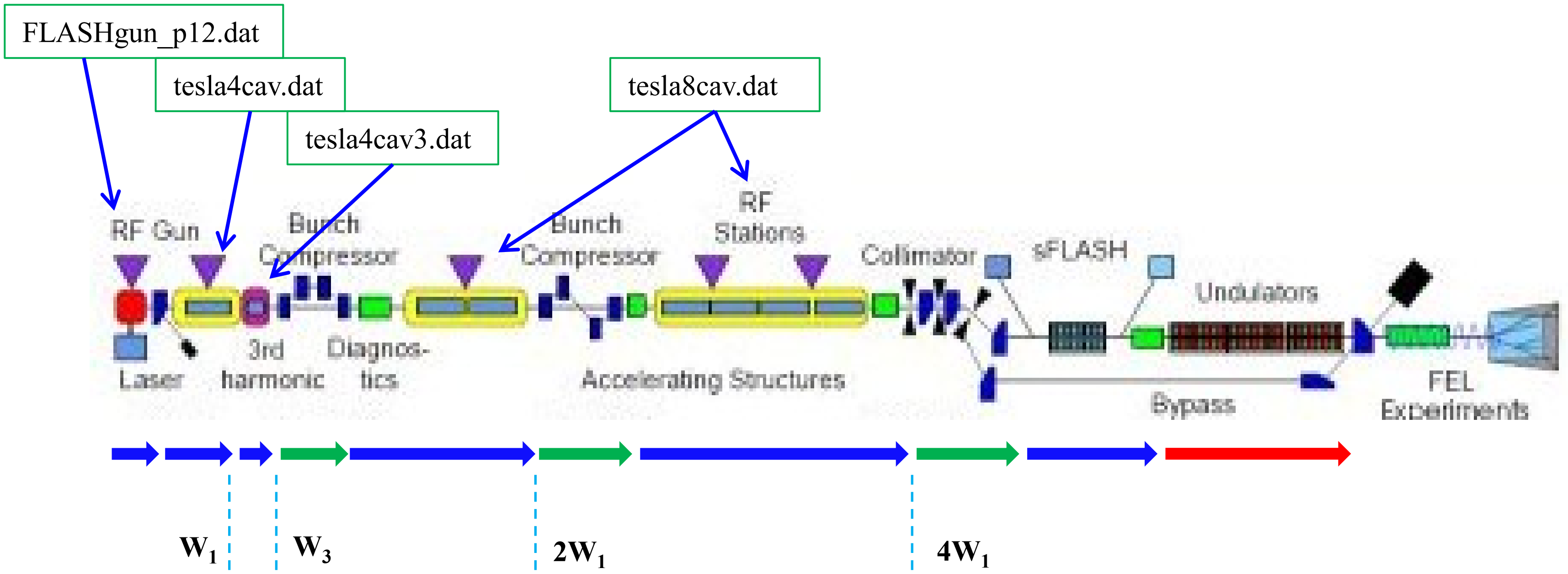


* ELEGANT lattice file for FLASH, FLASH_2012_1200MeV.lte

Start to end simulation of FLASH in two cases

Codes used during the simulation

RF Gun	ASTRA
ACC1	ASTRA
ACC39	ASTRA
BC2	CSR-TRACK
ACC2/3	ASTRA
BC3	CSR-TRACK
ACC4/5/6/7	ASTRA
Dogleg section	CSR-TRACK
Straight section before undulator	ASTRA
Radiation Calculation	GENESIS
Design optics calculation	ELEGANT
Beam optics matching	MAD8



ASTRA (tracking with space charge)

CSRtrack (tracking with CSR, 1D projected field calculation method)

GENESIS (Radiation calculation)

W1 -TESLA cryomodule wake
W3 - ACC39 wake

- **Initial parameters values of beam bunch** (300000 particles)

Charge	σ_t (Gaussian distribution)	σ_x (Radial uniform)	σ_y (Radial uniform)
0.22nC	4.4ps	0.286mm	0.286mm

- **Curvature radius of the reference trajectory in the compressors***

$$r_{BC2} = 1.6272 \frac{E_{BC2}}{151} \times \frac{73.2}{I_{BC2}}$$
$$r_{BC3} = 6.5185 \frac{E_{BC3}}{470} \times \frac{56.4}{I_{BC3}}$$

* Estimation formula from Martin Dohlus

- **RF parameters' values during the simulation**

Case1

Element	Phase shift	V_{max}
RF Gun	2.00°	
ACC1	5.43°	161.42MV
ACC39	170.1°	19.49MV
ACC2/3	18.40°	321.011MV
ACC4/5	0°	225.6MV
ACC6/7	0.0°	0.0MV

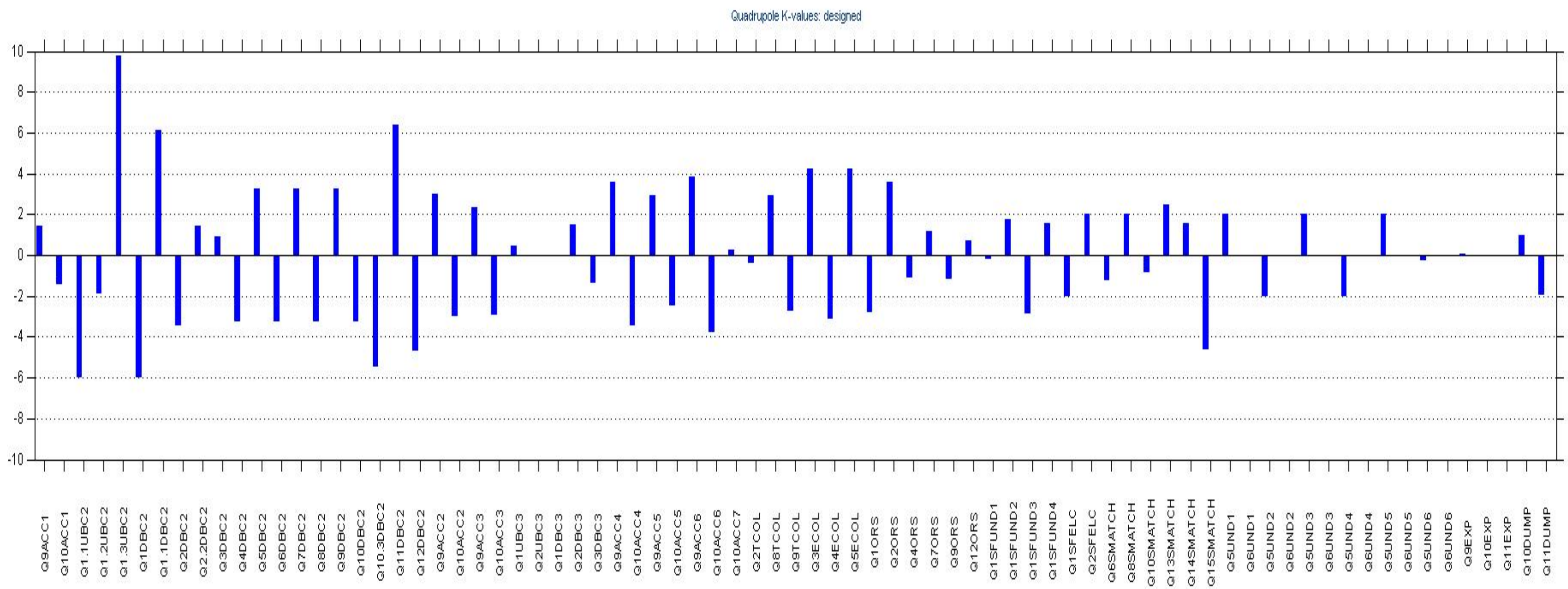
Case2

Element	Phase shift	V_{max}
RF Gun	2°	
ACC1	15.26°	166.6MV
ACC39	197.79°	20.188MV
ACC2/3	18.50°	321.198MV
ACC4/5	0°	225.6MV
ACC6/7	0.0°	0.0MV

- **Beam energy**

End of the element	Beam Energy	
	Case1	Case2
ACC1	165.23MeV	165.20MeV
ACC39	146.0MeV	146.0MeV
ACC2/3	450.0MeV	450.0MeV
ACC4/5/6/7	674.8MeV	674.5MeV

- **Field strength of the quadrupole magnets***

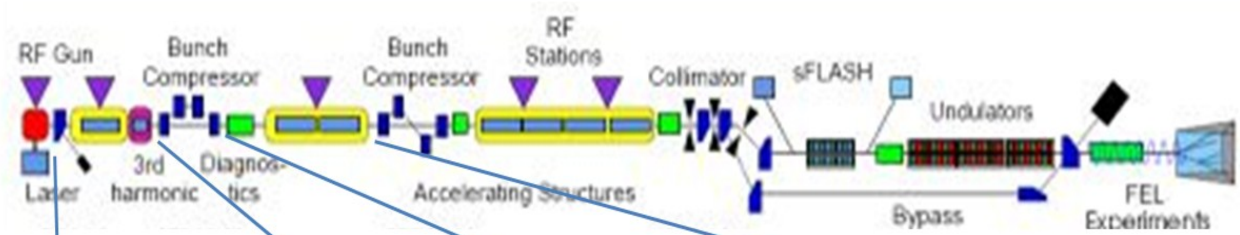


✓ As a normal operation mode, in case1, the beam optics is matched to the design optics before BC2 by adjusting Q_{9ACC1}, Q_{10ACC1}, $Q_{1.1UBC2}$ and $Q_{1\cdot 2UBC2}$.

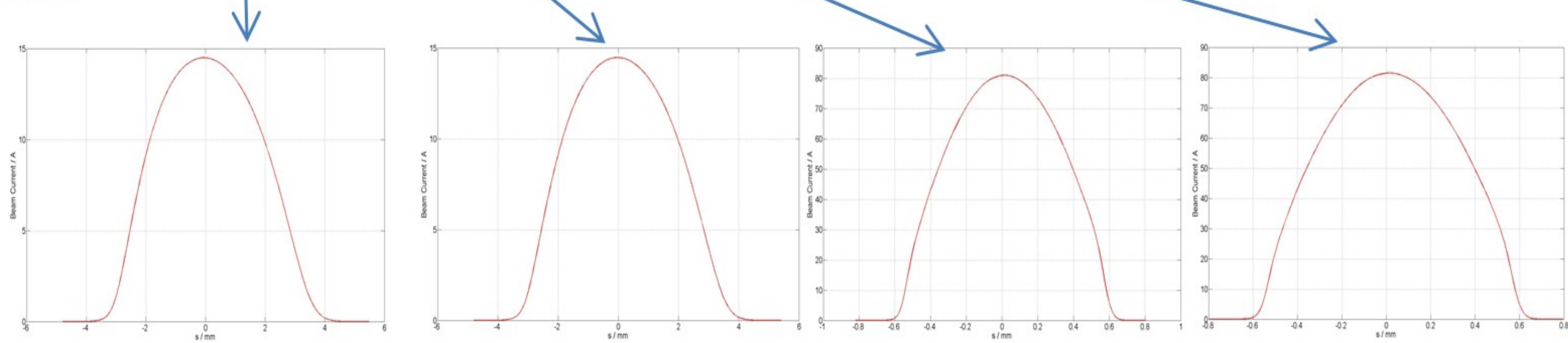
✓ In case2, the same field gradient ($k = \frac{\partial B_y}{\partial x}$) of the quadrupoles as in Case1 should be used.

* ELEGANT lattice file for FLASH, FLASH_2012_1200MeV.lte, med_med_FEL.sdds

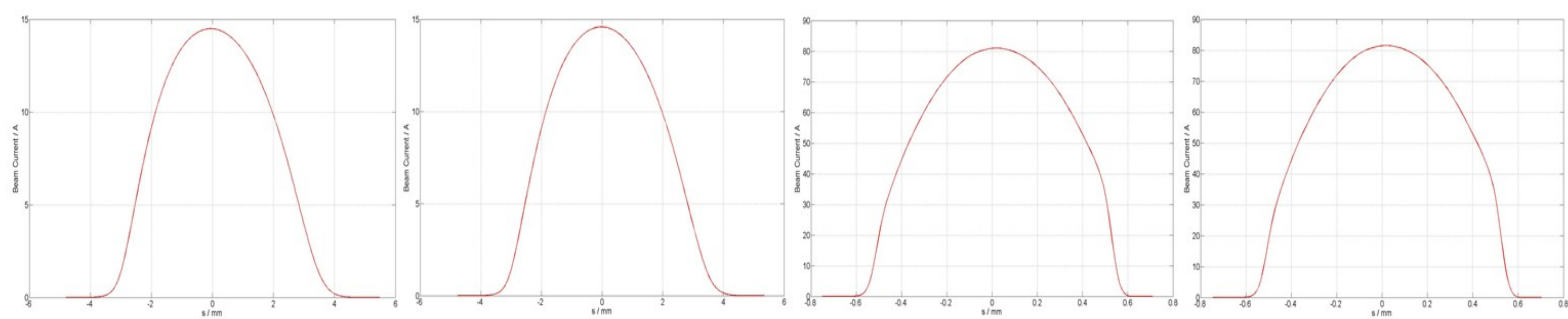
Beam current profile along the beam line

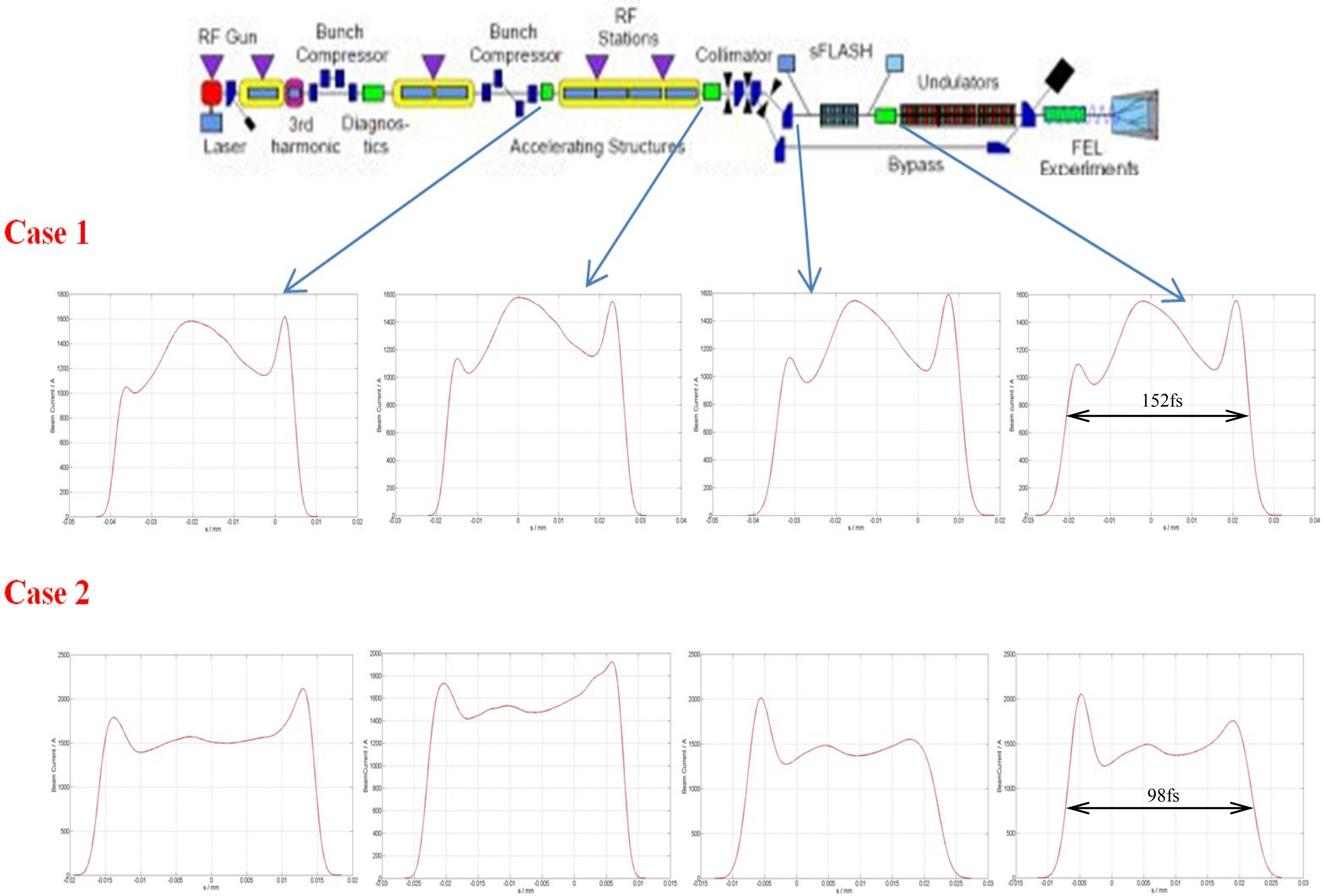


Case 1



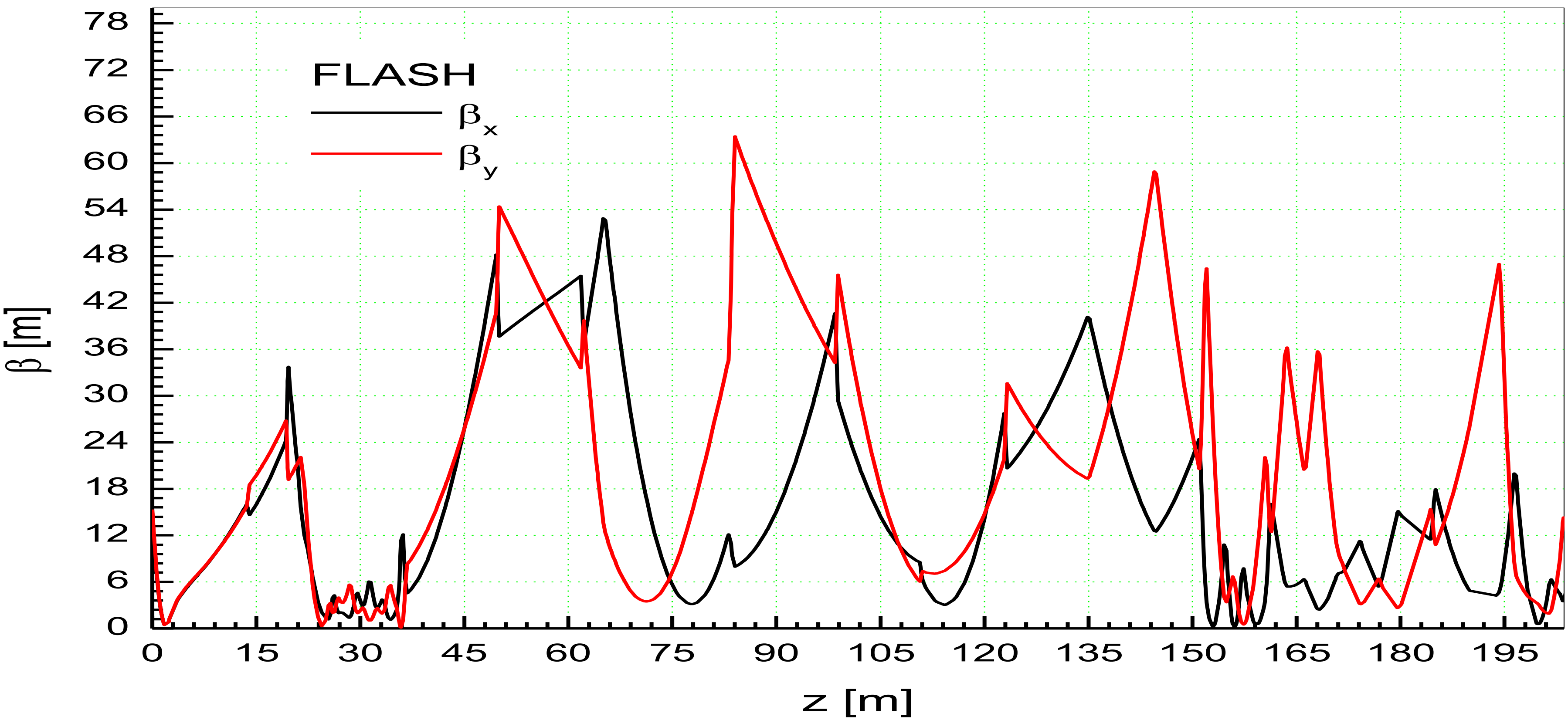
Case 2





RF Gun
Laser
3rd harmonic
Bunch Compressor
Diagnos-tics
Bunch Compressor
RF Stations
Accelerating Structures
Collimator
sFLASH
Undulators
Bypass
FEL Experiments
Case 1
152fs
Case 2
98fs

Analyzing the two cases' beam optics mismatching to the design optics



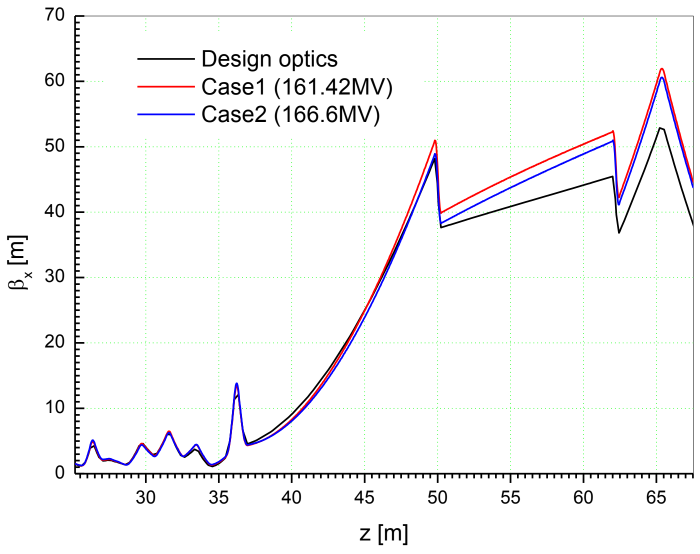
Design optics

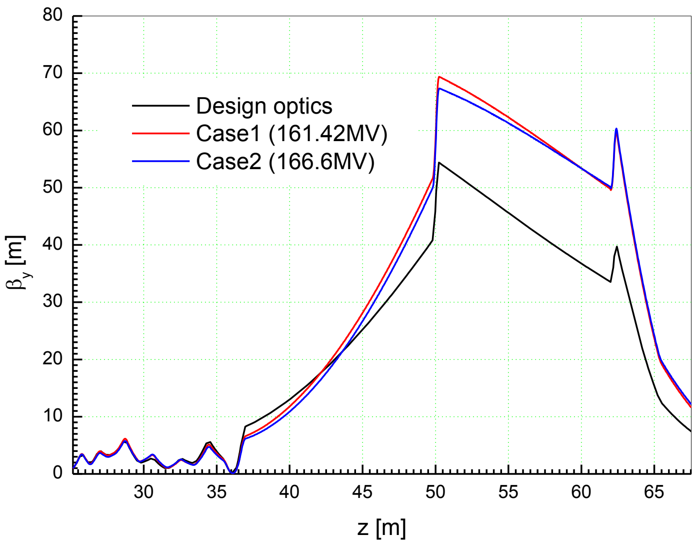
- **At the entrance of BC2**

Design Optics		Case1		Bmag
β_x [m]	α_x	β_x [m]	α_x	
22.3665	4.285583	22.40	4.26	**1.00051**
β_y [m]	α_y	β_y [m]	α_y	
21.0487	-0.84354	21.0	-0.834	**1.00003**

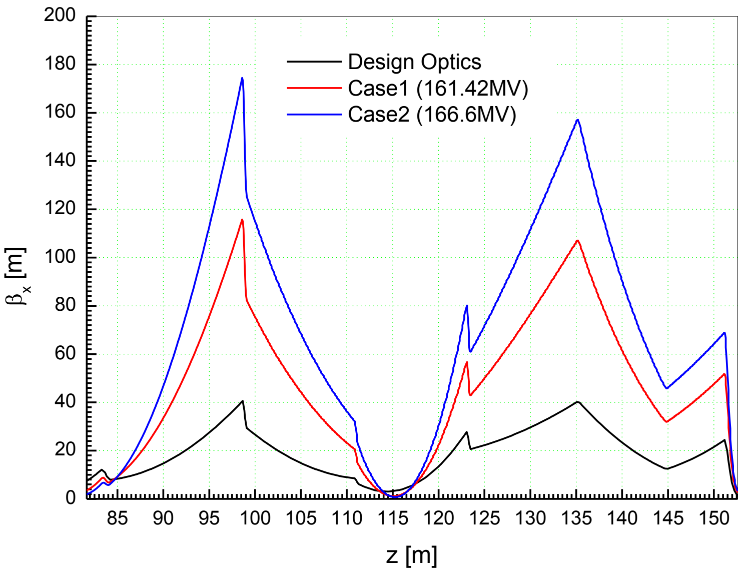
Design Optics		Case2		Bmag
β_x [m]	α_x	β_x [m]	α_x	
22.3665	4.285583	21.6	4.11	**1.00103**
β_y [m]	α_y	β_y [m]	α_y	
21.0487	-0.84354	20.1	-0.776	**1.00152**

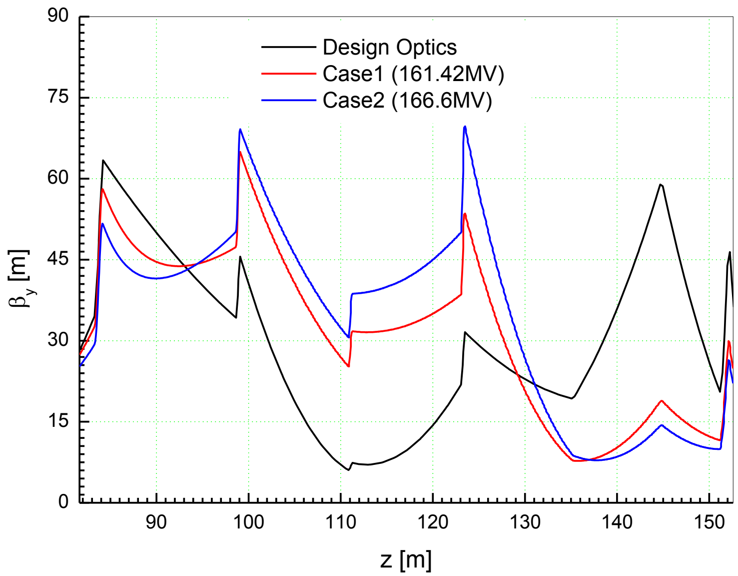
- **From the end of BC2 to the entrance of BC3**



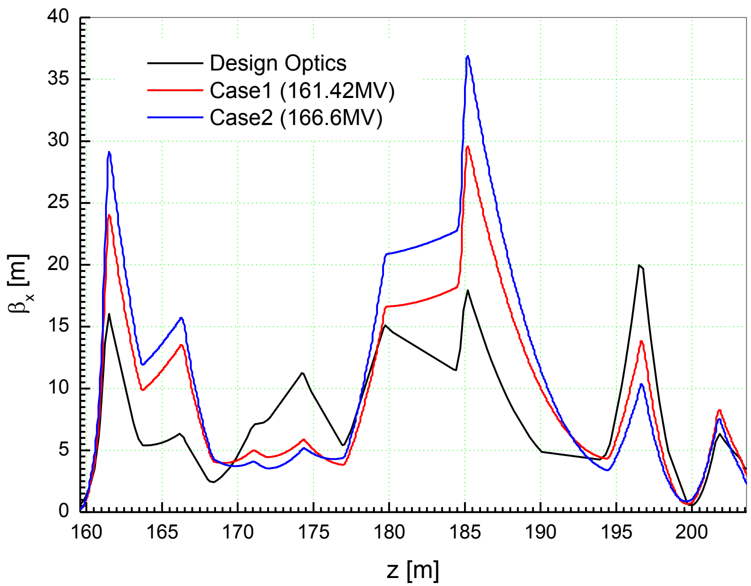


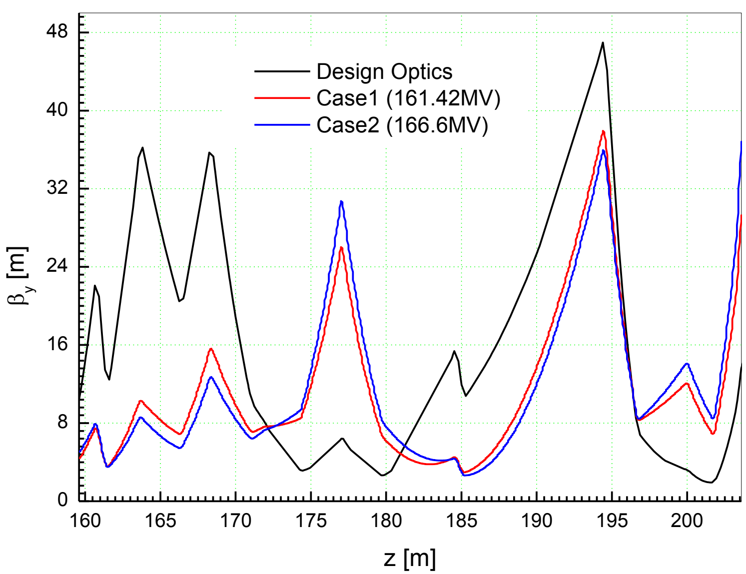
- **From the end of BC3 to the entrance of dogleg**



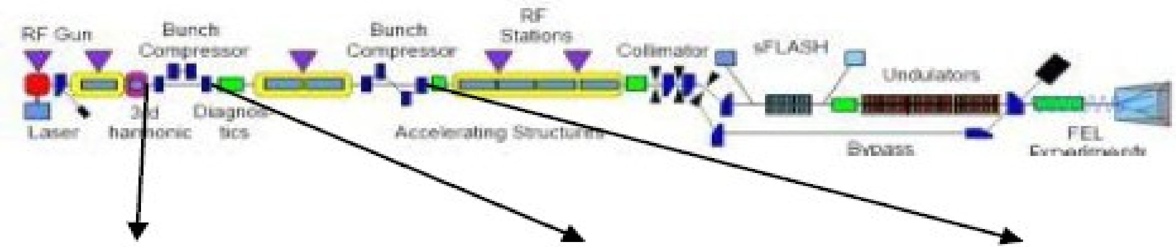


- **From the end of dogleg to the entrance of undulator**

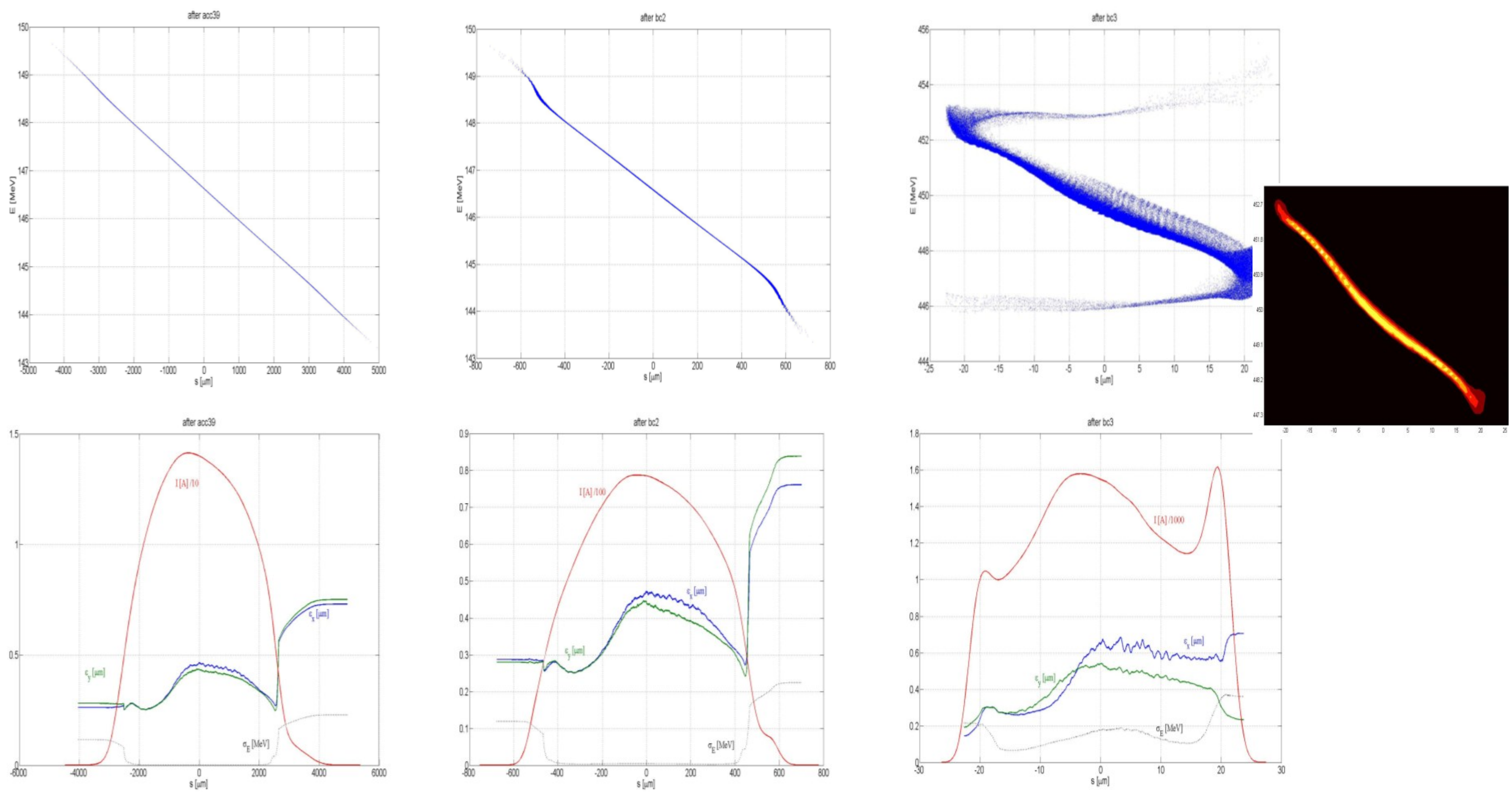




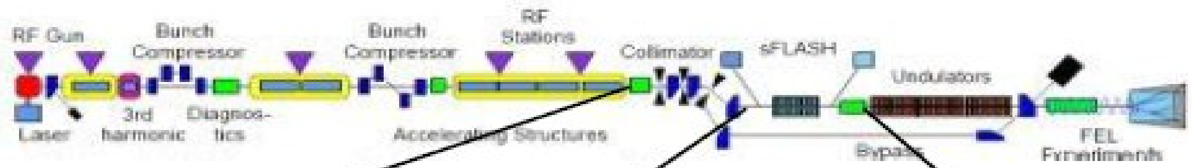
Slice analysis of the beam bunch



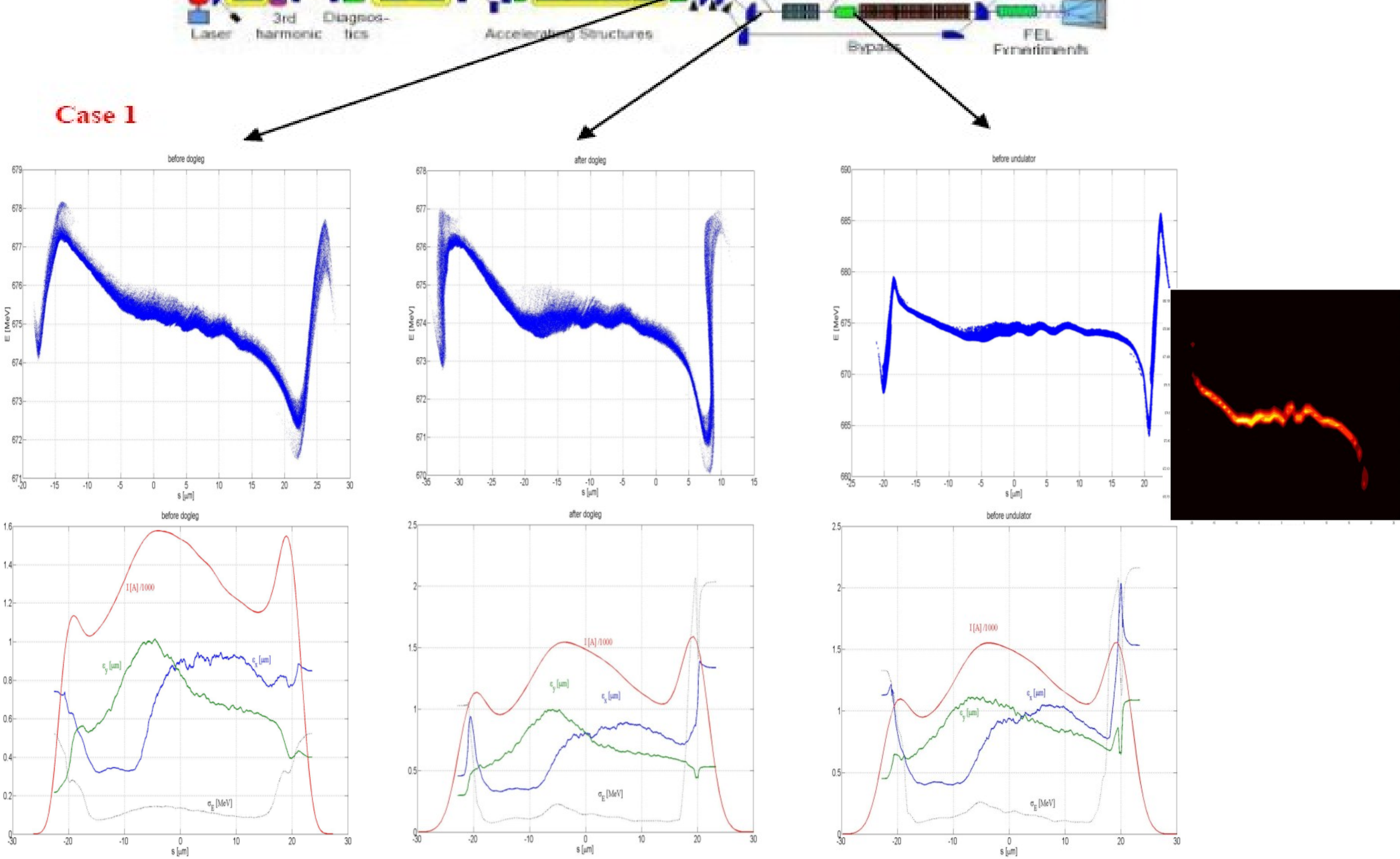
Case 1



$\varepsilon_x{}^{proj}$=0.61μm , $\varepsilon_y{}^{proj}$=0.61μm $\varepsilon_x{}^{proj}$=0.62μm , $\varepsilon_y{}^{proj}$=0.63μm $\varepsilon_x{}^{proj}$=1.26μm , $\varepsilon_y{}^{proj}$=0.69μm

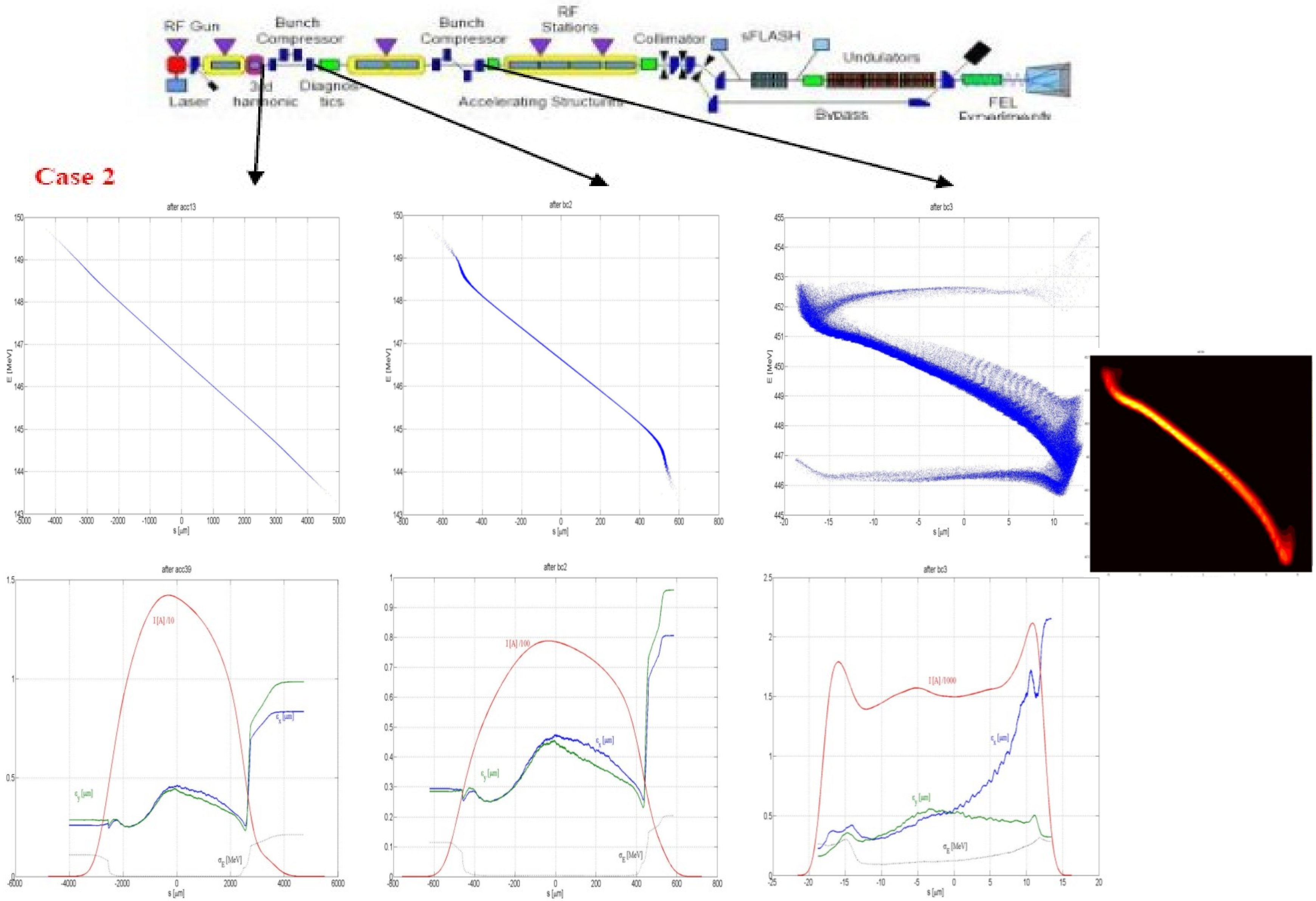


Case 1



$\varepsilon_x{}^{proj}$=1.59μm , $\varepsilon_y{}^{proj}$=0.79μm $\varepsilon_x{}^{proj}$=1.27μm , $\varepsilon_y{}^{proj}$=0.81μm $\varepsilon_x{}^{proj}$=2.05μm , $\varepsilon_y{}^{proj}$=1.01μm

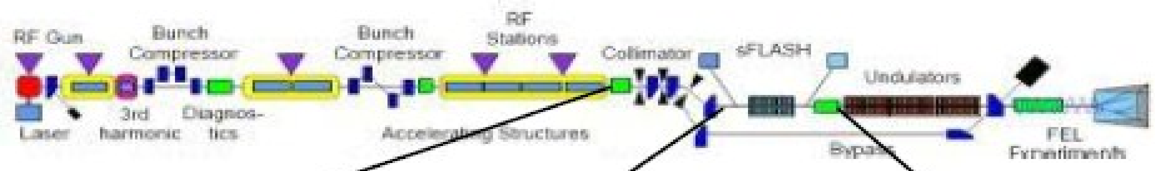
Case 2



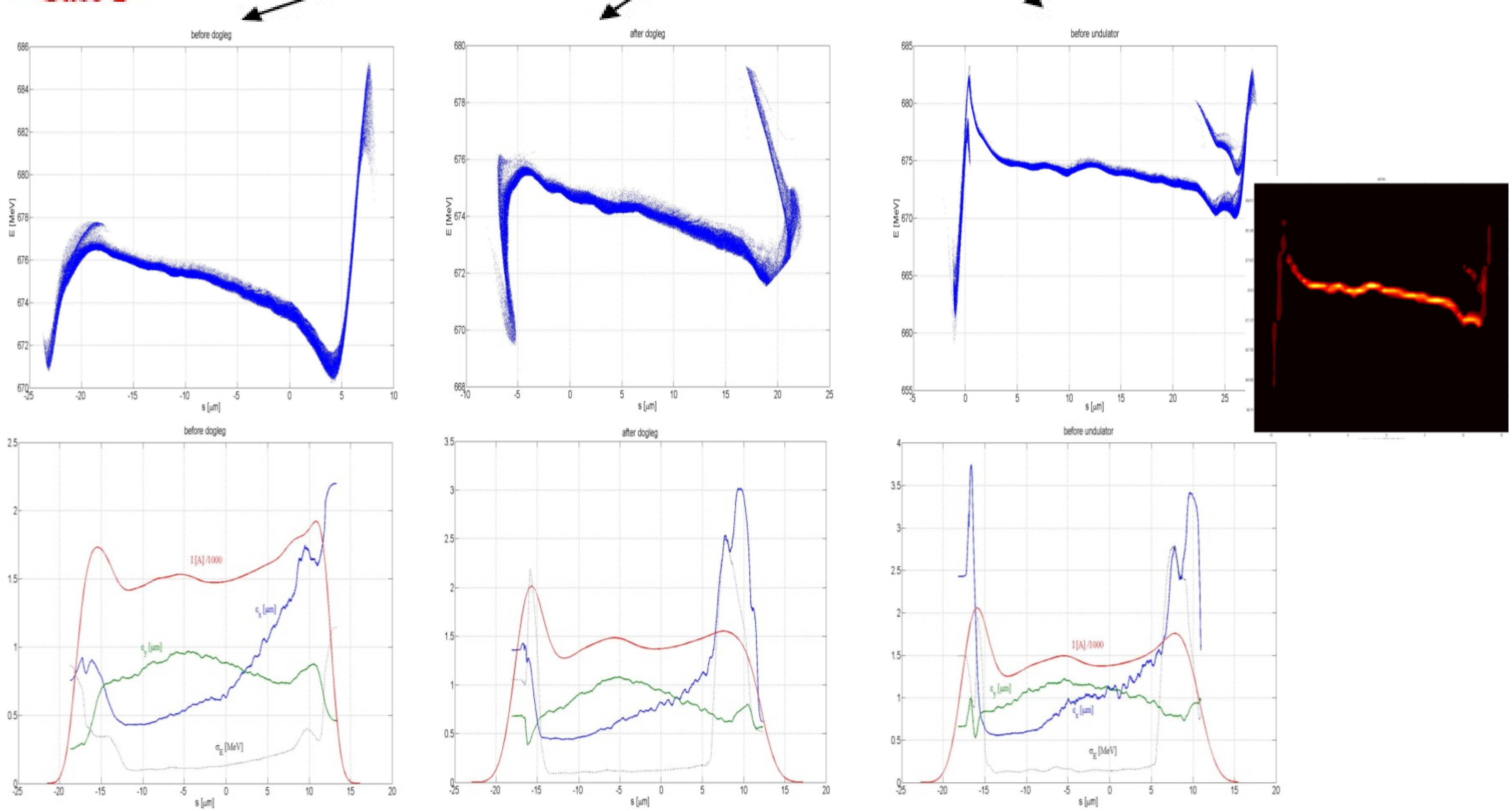
$\varepsilon_x{}^{proj}$=0.61μm , $\varepsilon_y{}^{proj}$=0.63μm

$\varepsilon_x{}^{proj}$=0.62μm , $\varepsilon_y{}^{proj}$=0.65μm

$\varepsilon_x{}^{proj}$=2.12μm , $\varepsilon_y{}^{proj}$=0.69μm



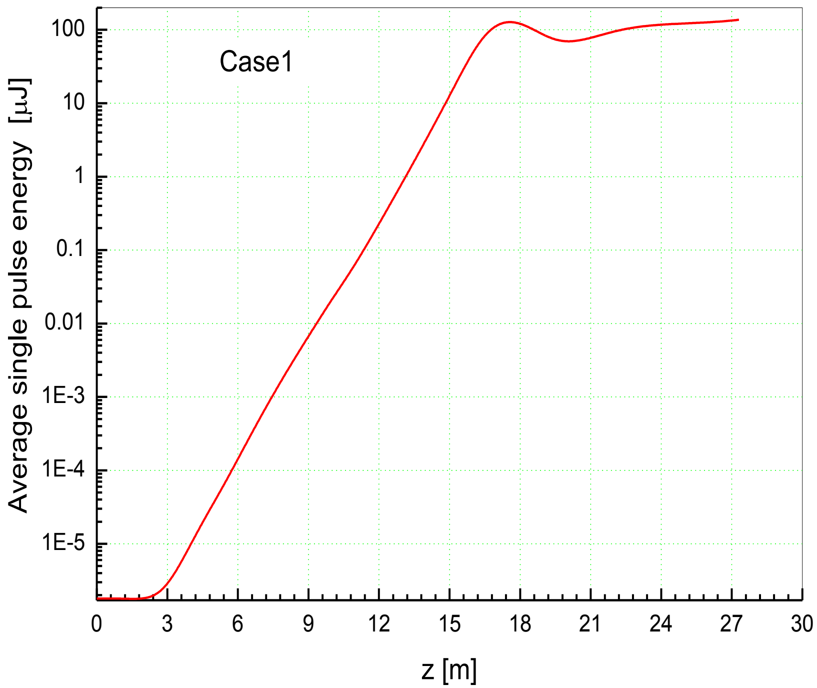
Case 2

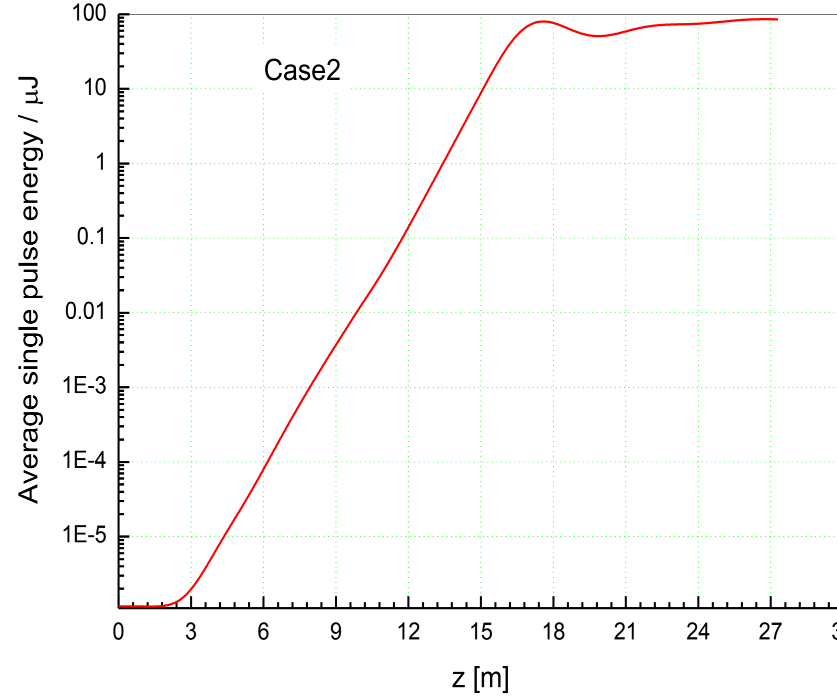


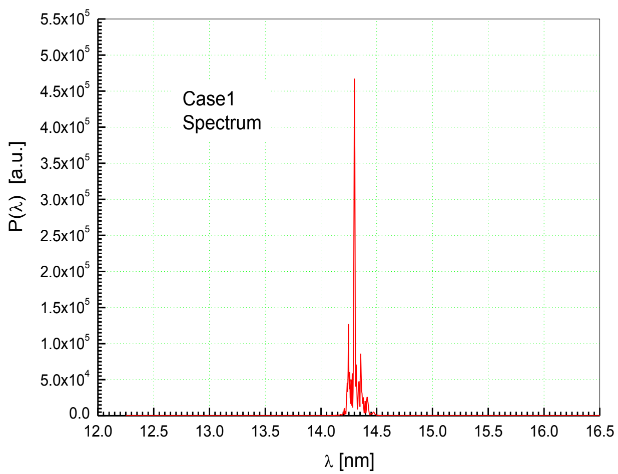
$\varepsilon_x{}^{proj}$=4.13μm , $\varepsilon_y{}^{proj}$=1.14μm $\varepsilon_x{}^{proj}$=4.18μm , $\varepsilon_y{}^{proj}$=1.14μm $\varepsilon_x{}^{proj}$=6.20μm , $\varepsilon_y{}^{proj}$=1.29μm

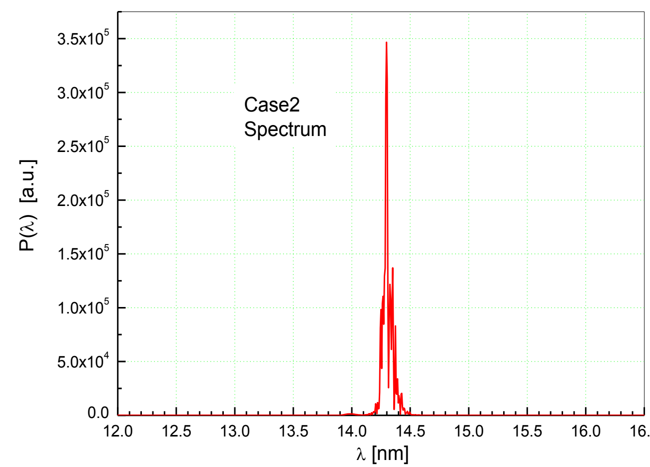
SASE FEL simulations

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









Summary

1. In order to investigate the ACC1 voltage amplitude changing impact on SASE at FLASH, two cases have been studied.

   * In case1, RF parameters values of the accelerating modules are closed to the setting points of the logbook.

   * In case2, in order to get the same beam energy (146MeV) after ACC39, the same compression ratio in BC2 and almost the same symmetry of the current profile as in case1, RF parameters have been obtained after theoretical calculation.

2. After optimizing the RF parameters of the accelerating modules, one should be able to achieve SASE even if the voltage amplitude of ACC1 is adjusted from about 161MV to 166MV and there is no quadrupole field strength adjustment.

Acknowledgements *to*

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Martin Dohlus,

Winni Decking

for their kind help and helpful discussions

Thank you for your attention!