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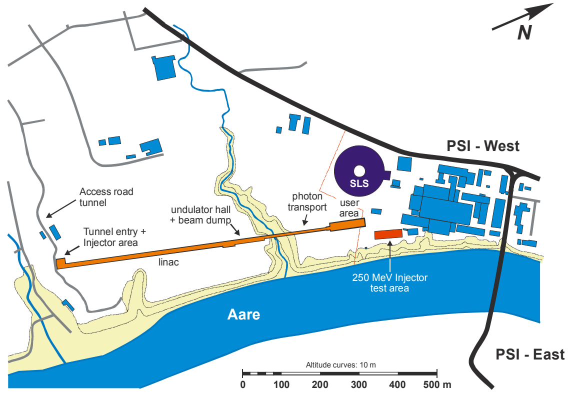

Design Concepts and Performance of 6 GeV PSI-XFEL LINAC with CTF3 GUN

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PSI XFEL-2008-22

Outline

- ☐ Review on Possibility of Compact XFEL facilitiy with CTF3 RF Gun
- ☐ Optimized 250 MeV Injector
- ☐ Design Concepts & Layout of BCs, DIAGs, LINACs
- ☐ Five Linac Optimizations for the PSI-XFEL Project
- ☐ Possible Solutions to reduce Linac Length
- ☐ Summary & Acknowledgements

Preparing PSI-XFEL Facility

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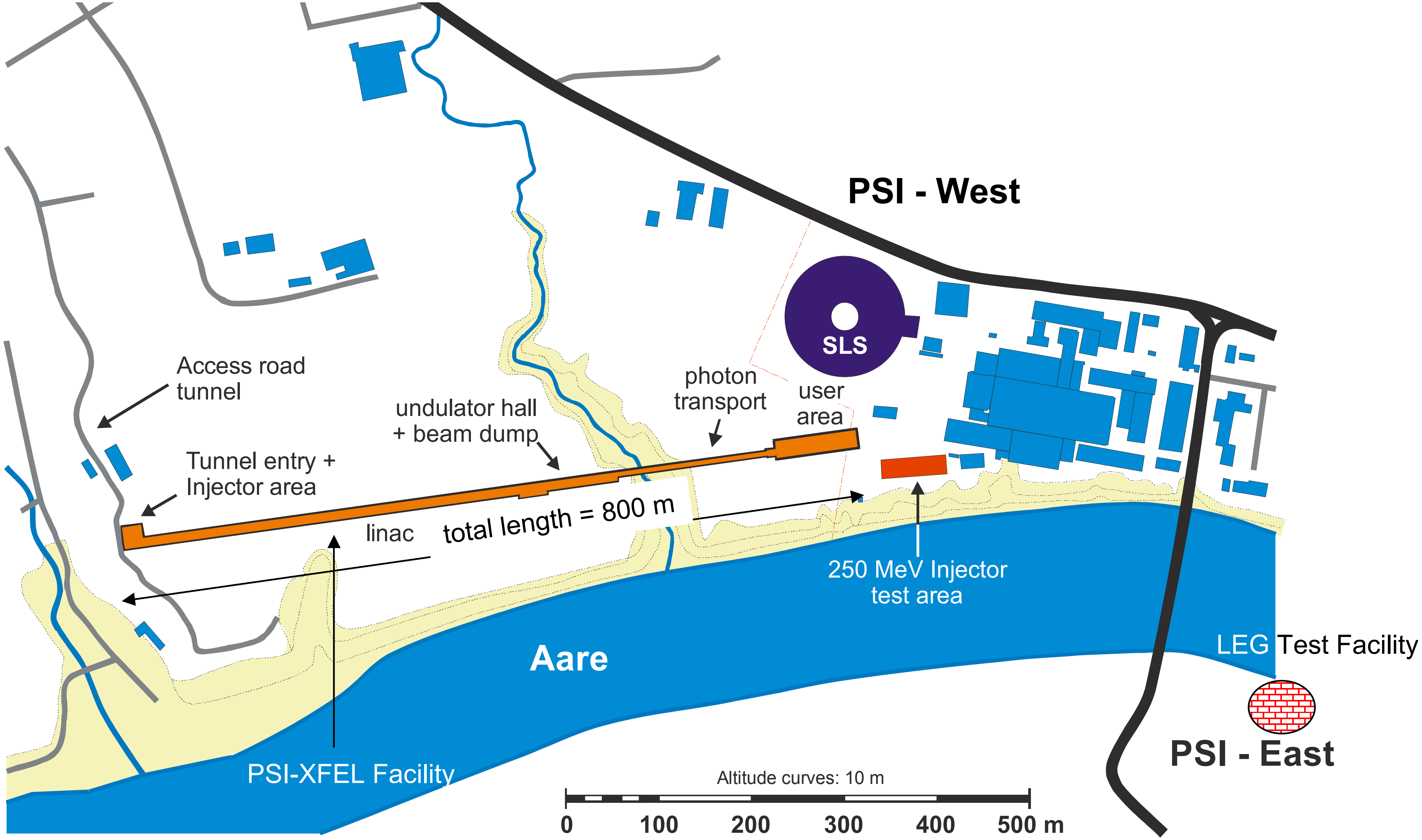
2003-2011 : Pulser based Advanced Low Emittance Gun (LEG) Test Facility - Operating

2008-2011 : 250 MeV Injector Test Facility - Commissioning will be started in January, 2010

2011-2016 : LEG + Short Linac + Cryo In-Vacuum Undulator based 6 GeV PSI-XFEL Facility



Present Parameters for PSI-XFEL Project

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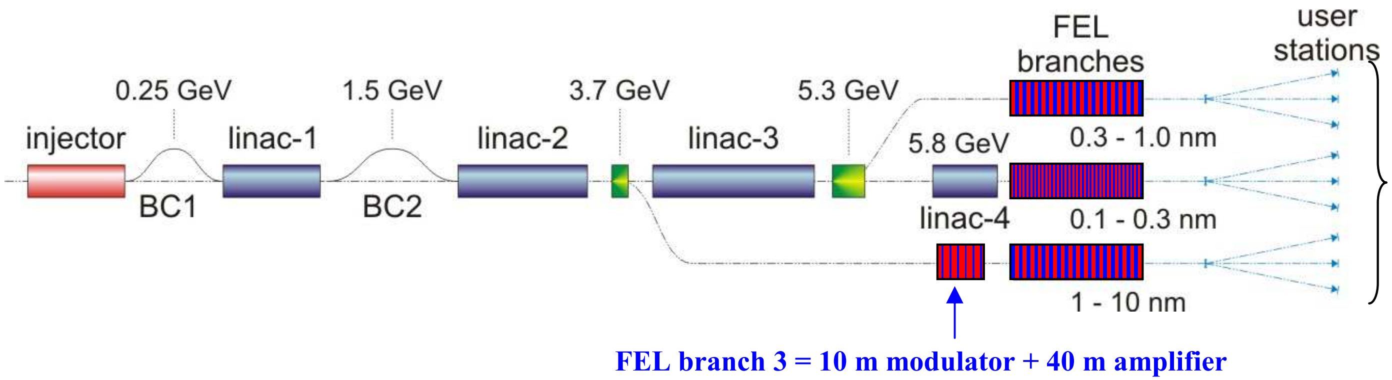
Ultra-low Emittance + Normal Conducting Short Linac + Cryo In-Vacuum Undulator



- photon pulse duration < 30 fs (rms)
- photons per pulse = 10^{11} - 10^{12}
- bandwidth of HGHG mode ~ 0.05% (FWHM)
- undulator for branch 1 = Cryo In-Vacuum
- undulator length < 60 m

FEL Branch 3 (1 - 10 nm) will be operated with the SASE mode as well as the HHG based Seeded HGHG mode

LEG based Parameters for the SASE mode

	branch 1	branch 2	branch 3	
beam energy	3.3 – 5.8	3.3 – 5.3	3.7	GeV
beam peak current	1.5	1.5	1.5	kA
normalized slice emittance	0.2	0.2	0.2	μm
RMS slice energy spread	500	500	500	keV
repetition rate	10 – 100	10 – 100	10 – 100	Hz
undulator period	15	36	52	mm
undulator a_u	1.2	1 - 2.4	1 - 2.3	
target wavelength range	0.1 – 0.3	0.3 – 1	1 – 10	nm
photon energy range	12 – 4	4.4 – 0.39	1.2 – 0.13	keV
peak brilliance	10^{32} - 10^{33}	10^{32} - 10^{33}	10^{31} - 10^{32}	ph/s/mm²/mrad²/0.1% BW
polarization	linear	linear/circular	linear/circular	-

Advanced LEG Test Facility for PSI-XFEL

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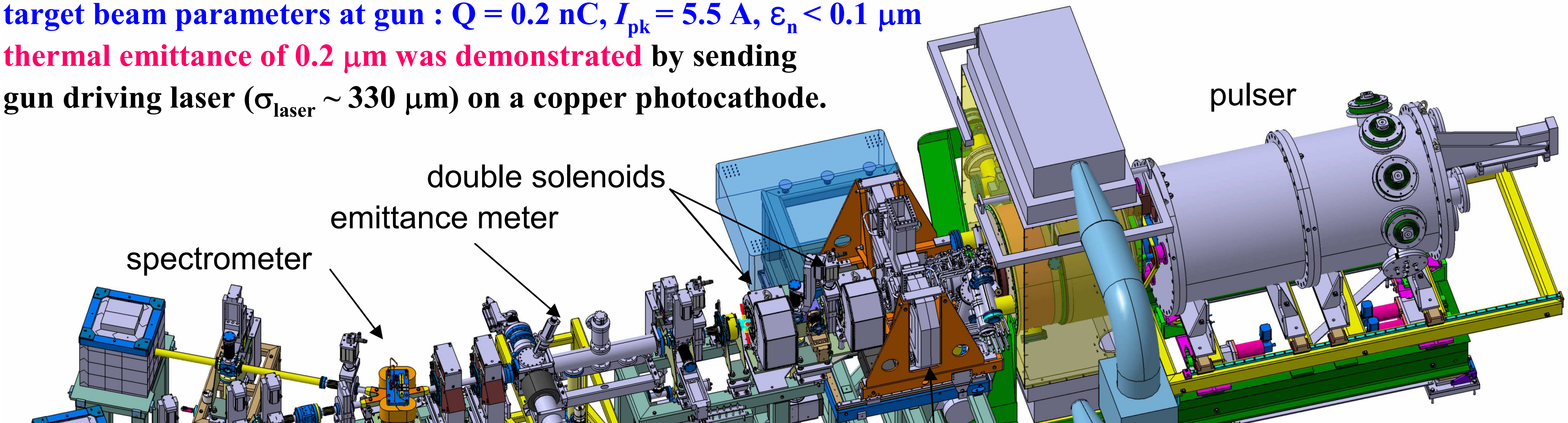
Low Emittance Gun (LEG) Test Facility - 500 keV Phase-I (2003 - 2008) and 4 MeV Phase-II (2008-2011)

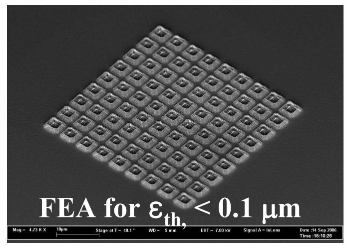
LEG = 1 MV pulser supplying max. gradient of 250 MV/m at 4 mm gap + Field Emitter Array (FEA) cathode

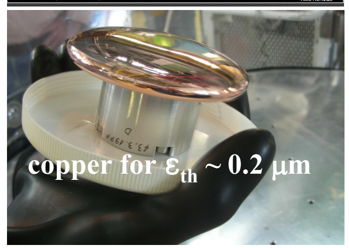
Beams are accelerated to 4 MeV and the longitudinal phase space is compensated by a two frequency RF cavity

target beam parameters at gun : Q = 0.2 nC, I_{pk} = 5.5 A, $\varepsilon_n < 0.1$ μm

thermal emittance of 0.2 μm was demonstrated by sending gun driving laser ($\sigma_{laser} \sim 330$ μm) on a copper photocathode.







3D Layout of 4 MeV LEG Phase-II
(commissioning in November 2008)

Advanced LEG Vs. CTF3 RF Gun

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Advanced LEG based 6 GeV linac

it seems that we need more time to demonstrate the excellent performance of the LEG:
- **ultra-low slice emittance of 0.2 μm**
- **low peak current of 1.5 kA**
- **higher rms slice energy spread of 500 keV due to an ultra-high compression factor of 273**

CTF3 RF Gun based 6 GeV linac

it seems that we may save time to demonstrate the good performance of the RF gun:
- **still low slice emittance of about 0.33 μm**
- **high peak current of about 2.7 kA**
- **lower rms slice energy spread of about 210 keV due to a low compression factor of 123**

$$P = P_o \exp(z / L_G) \qquad L_{sat} \approx L_G \ln\left(\frac{P_{sat}}{\rho E e \Delta\omega}\right) \approx 20 L_G \qquad L_G \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho} \qquad \Delta\lambda / \lambda \sim 2\rho$$

$$\rho \approx \frac{1}{4}\left[\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_n}\left(\frac{K}{\gamma}\right)^2\right]^{1/3} \qquad \lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \; K \approx 0.934 B_o[\mathrm{T}]\lambda_u[\mathrm{cm}]$$

higher ρ ⇨ shorter L_G ⇨ shorter saturation length L_{sat} ⇨ shorter undulator

LEG gives $I_{pk} / \varepsilon_n \sim$ 7.5 while CTF3 RF gun can give $I_{pk} / \varepsilon_n \sim$ 8.2 with 2.7 kA

Advanced LEG Vs. CTF3 RF Gun

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With the CTF3 RF gun based 6 GeV linac, ρ can be high enough !
It seems that we can build a compact XFEL facility with CTF3 RF gun !

- low peak current of 1.5 kA
- higher rms slice energy spread of 500 keV due to an ultra-high compression factor of 273

CTF3 RF Gun based 6 GeV linac

it seems that we may save time to demonstrate the good performance of the RF gun:

- still low slice emittance of about 0.33 μm
- high peak current of about 2.7 kA
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LEG gives $I_{pk} / \varepsilon_n \sim 7.5$ while CTF3 RF gun can give $I_{pk} / \varepsilon_n \sim 8.2$ with 2.7 kA

Optimized 250 MeV Injector Test Facility

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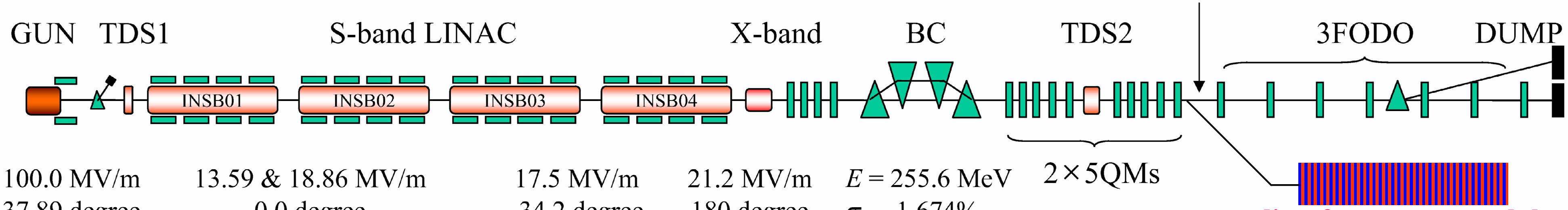
Layout of CTF3 RF Gun based 250 MeV Injector Test Facility (2008-2011)

laser beam : $\sigma_{x,y}$ = 270 μm, ΔT = 9.9 ps (FWHM), rise & falling time = 0.7 ps
e-beams : Q ~ 0.2 nC, $\varepsilon_{thermal}$ = 0.195 μm, I_{peak} = 22 A

σ_z = 840 μm ⟶ 58 μm

E = 255.5 MeV, σ_δ = 1.665%
σ_x ~ 55 μm, σ_y ~ 55 μm, σ_z ~ 58 μm
ε_{nx} ~ 0.379 μm, ε_{ny} ~ 0.350 μm



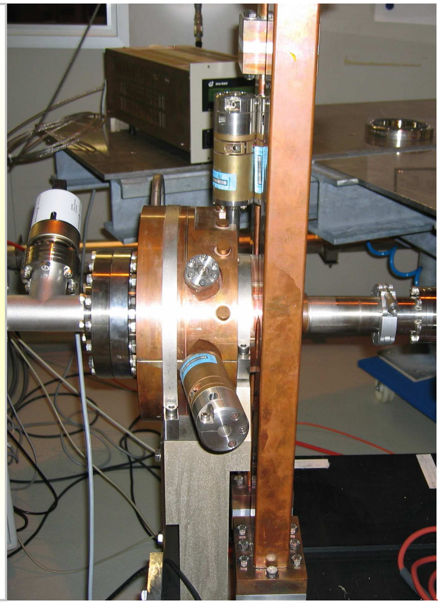
GUN	S-band LINAC	S-band LINAC	X-band	BC
100.0 MV/m	13.59 & 18.86 MV/m	17.5 MV/m	21.2 MV/m	E = 255.6 MeV
37.89 degree	0.0 degree	-34.2 degree	180 degree	σ_δ ~ 1.674%
from zero crossing			ΔE = -20 MeV	R_{56} = 46.8 mm
				θ = 4.1 deg

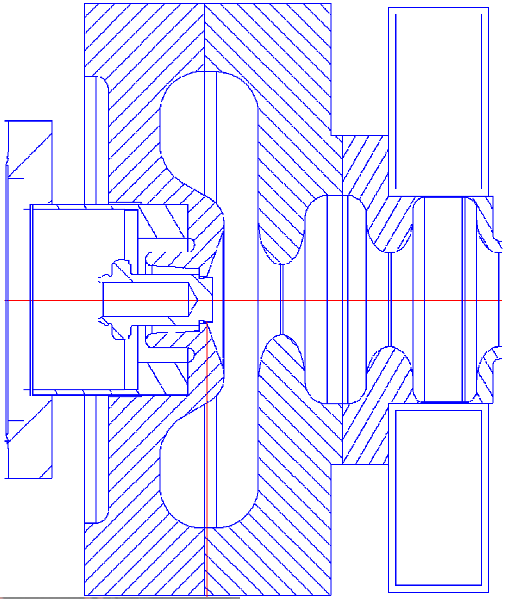
seeding & prototype undulator tests @ Phase-II

s = 0.0 m 2.95 m 12.3 m 32.839 m 43.339 m 51.75 m 56.89 m 65 m

CTF3 RF GUN

RF tested @ 100 MV/m - two weeks operation at CERN
power for 100 MV/m = 22 MW with 4.5 μs RF pulse
power for 120 MV/m = 25 MW
RF frequency ~ 2998.5 MHz
cell = 2.5 cells (One TM02 + Two TM01)
Q_0 = 16300
number of bunch in a train = 48
cathode wall angle = 20 degree
total length ~ 0.25 m
full cell length ~ 50 mm
designed charge ~ 2.33 nC for CTF3





Optimized 250 MeV Injector Test Facility

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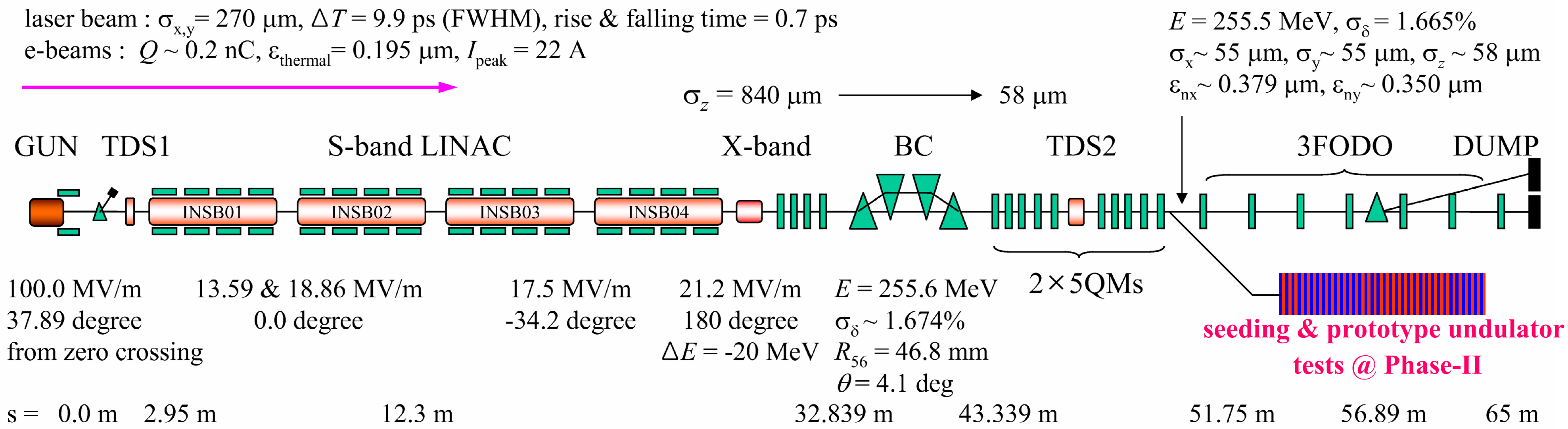
Layout of CTF3 RF Gun based 250 MeV Injector Test Facility (2008-2011)



250 MeV Injector will be built to develop various advanced accelerator, undulator, and FEL technologies for the coming 6 GeV PSI-XFEL project:

- **studying slice and projected emittance transportation along injector**
- **studying the invariant envelop matching and emittance damping in bootster linac**
- **studying bunch compression and Coherent Synchrotron Radiation (CSR) effects in a chicane**
- **developing slice beam parameter diagnostics technologies with LOLA cavities (TDS1 & TDS2) & 3 FODO cells**
- **developing ultra-stable RF low level system, timing system, and synchronization system**
- **developing beam based alignment technology and orbit and bunch length feedback system**
- **at the second phase, testing of prototype cryo in-vacuum undulator and HHG based external seeded FEL**

At the beginning phase, a CTF3 RF gun based RF photoinjector will be tested. Then the pulser based advanced LEG will be tested in the 250 MeV injector.

Meaningful Thermal Emittance

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- nsc and thermal emittance are the most biggest contributions in slice emittance
- We can reduce slice emittance by reducing thermal emittance on the cathode !

$$\varepsilon_{nx,ny} = \sqrt{\varepsilon_{th}^2 + \varepsilon_{lsc}^2 + \varepsilon_{nsc}^2 + \varepsilon_{rf}^2 + \varepsilon_{optics}^2} \qquad \varepsilon_{slice} \geq \varepsilon_{th}$$

$$\varepsilon_{th} \approx \sigma_{x,y}\sqrt{\frac{h\nu - \phi_0 + \phi_{\mathrm{schottky}}}{3m_e c^2}}, \quad \sigma_x = \sigma_y \ \text{ for a round beam}$$

Here $\phi_{\mathrm{schottky}} \sim 3.7947\times10^{-5}\sqrt{E(V/m)}$ eV

$$\varepsilon_{lsc} \propto \frac{Q}{(2\sigma_r + \sigma_z)E}$$

$$\varepsilon_{nsc} \propto \frac{FQ}{\sigma_r^2\sigma_z}$$

$$\varepsilon_{rf} \propto f_{rf}^2\sigma_r^2\sigma_z^2 E$$

$$\varepsilon_{optics} \propto \frac{\sigma_\delta\sigma_r^2}{f_{sol}}$$

D. H. Dowell *et al.*, PRST-AB 9, 063502 (2006)

K. L. Jensen *et al.*, Journal of Applied Physics 102, 074902 (2007)

C. Travier *et al.*, NIMA 340, 26 (1994)

- Expected Thermal Emittance from Q.E. Measurement

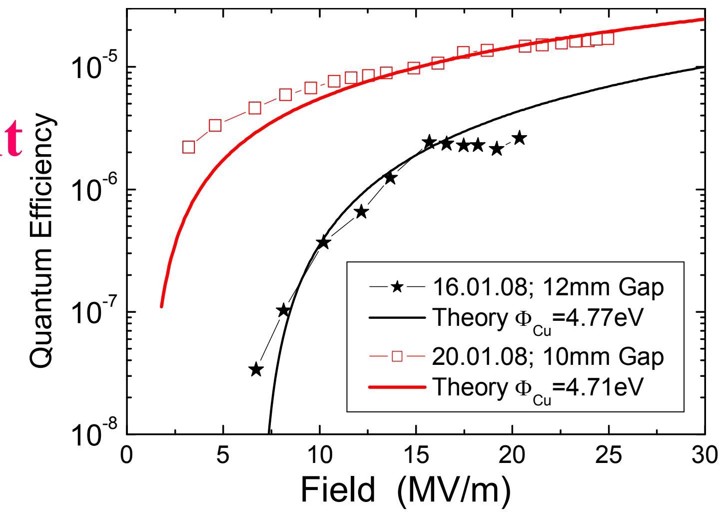
for a diamond turned copper, ϕ_0 = 4.71 eV

at 40 MV/m, ϕ_{schottky} ~ 0.240 eV, $h\nu$ = 4.66 eV

expected $\varepsilon_{th,40}$ ~ 0.12 μm for $\sigma_{x,y}$ ~ 330 μm

at 100 MV/m, ϕ_{schottky} ~ 0.380 eV, $h\nu$ = 4.66 eV

expected $\varepsilon_{th,100}$ ~ 0.15 μm for $\sigma_{x,y}$ ~ 330 μm



Laserprofile for Gun & Booster Optimization

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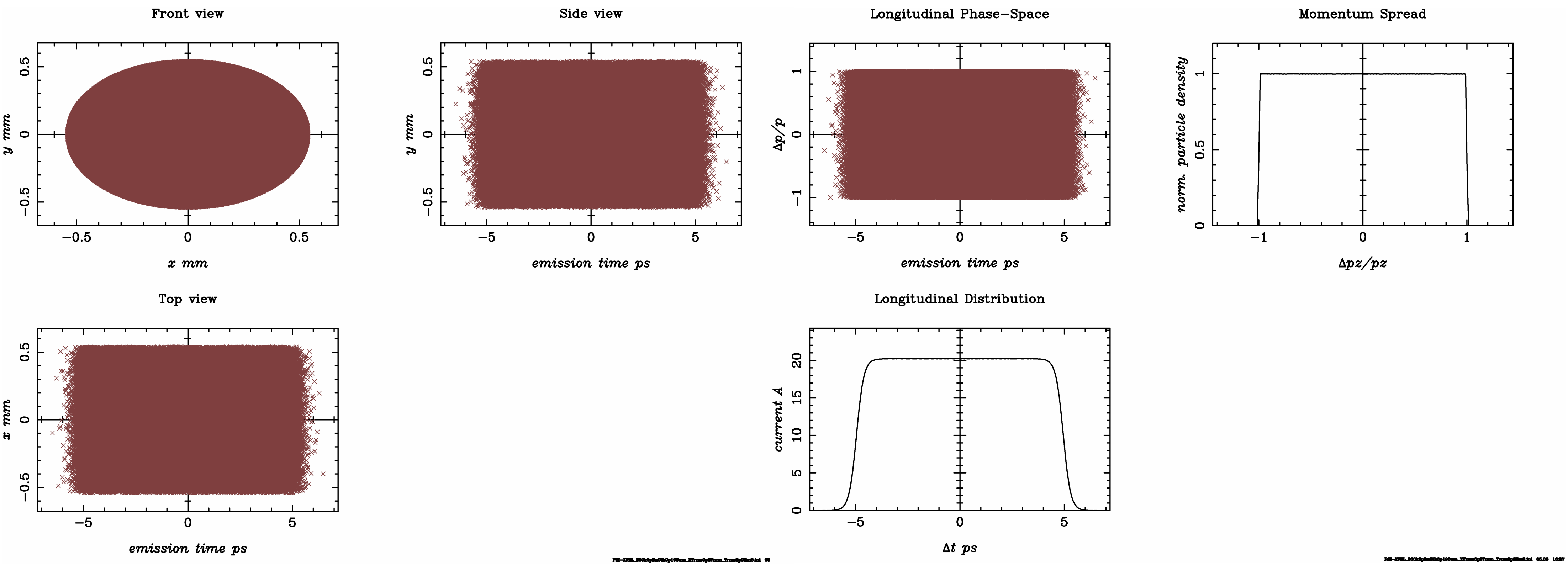
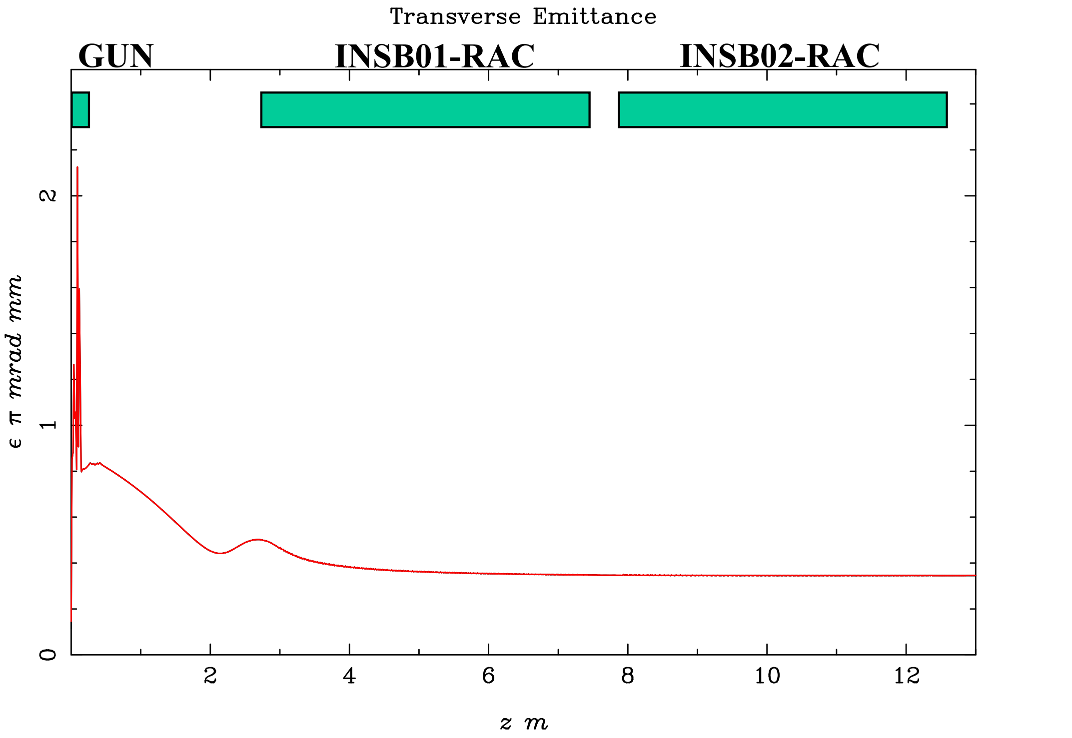
22 A - Low Project Emittance & Somewhat Low Slice Emittance
INSB01 @ 2.95 m

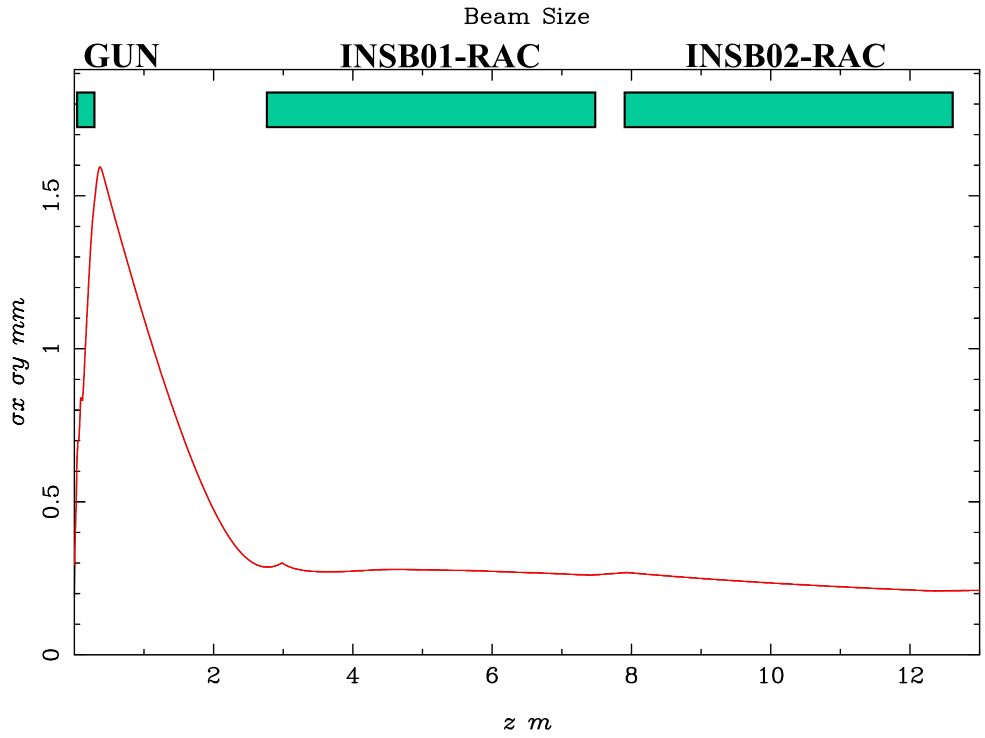


laser beam : $\sigma_{x,y}$ **= 270 μm,** ΔT **= 9.9 ps (FWHM), rising & falling time = 0.7 ps**
e-beams : $Q \sim$ **0.2 nC,** $I_{peak} \sim$ **22 A,** $\varepsilon_{thermal}$ **= 0.195 μm**

ASTRA Optimization along Gun & Booster

22 A - Low Project Emittance & Somewhat Low Slice Emittance
INSB01 @ 2.95 m





E = 149.394 MeV, σ_δ = 0.163%

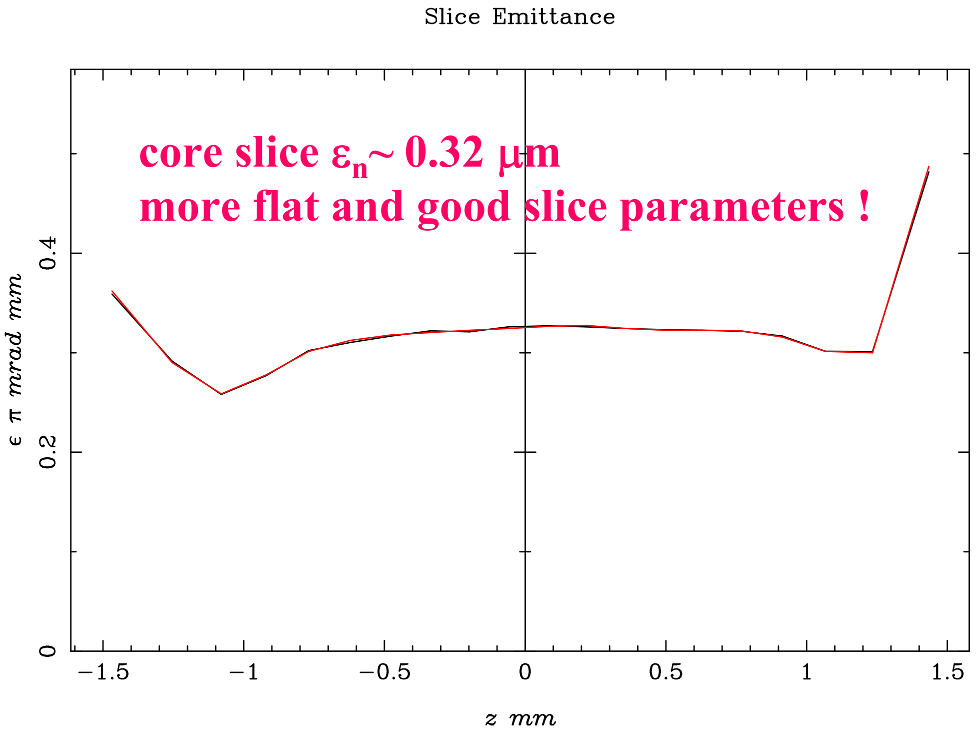
σ_x = 211 μm, σ_y = 211 μm, σ_z = 840 μm

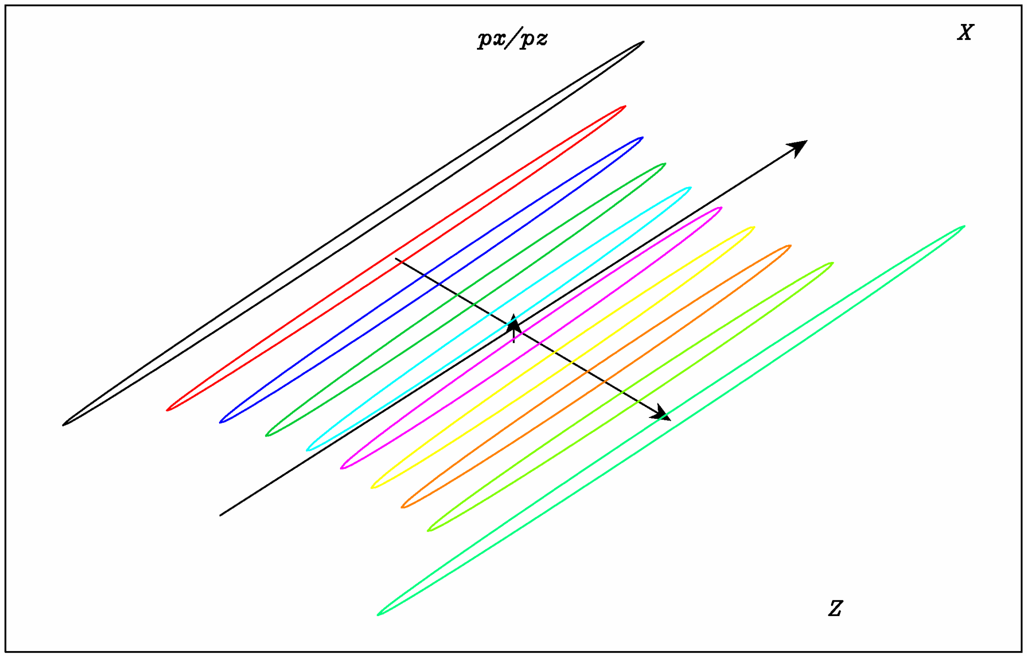
ε_{nx} = 0.345 μm, ε_{ny} = 0.345 μm

Q = 0.2 nC, I_{peak} ~ 22 A

ASTRA Optimization @ 13 m

22 A - Low Project Emittance & Somewhat Low Slice Emittance
INSB01 @ 2.95 m





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Q = 0.2 nC, I_{peak} ~ 22 A

ASTRA Optimization @ 13 m

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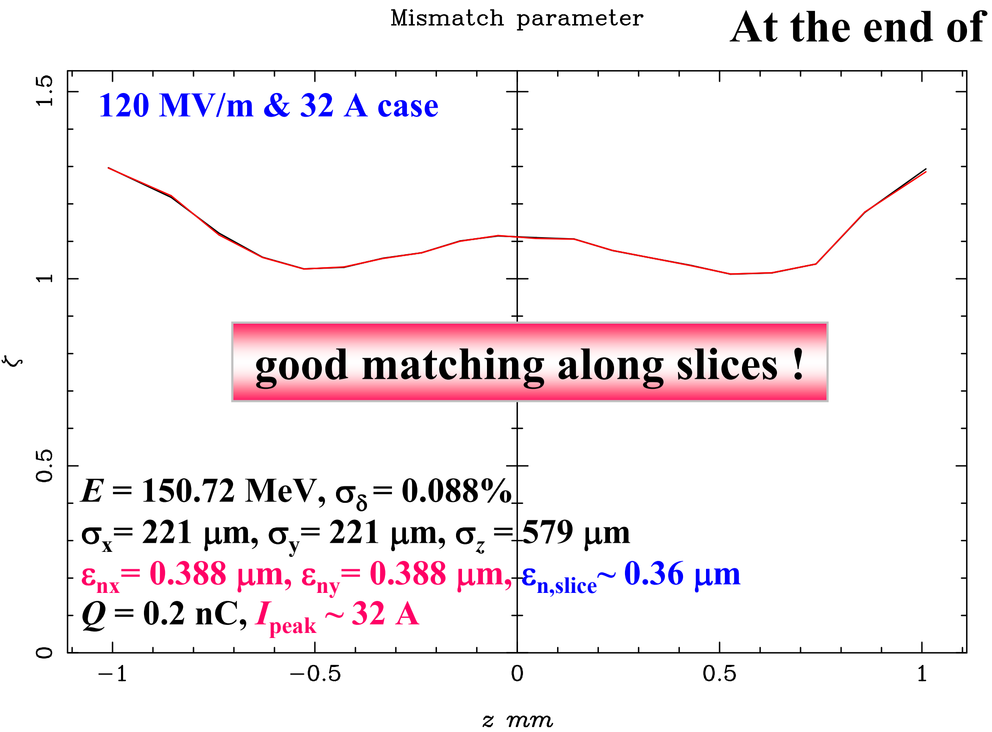
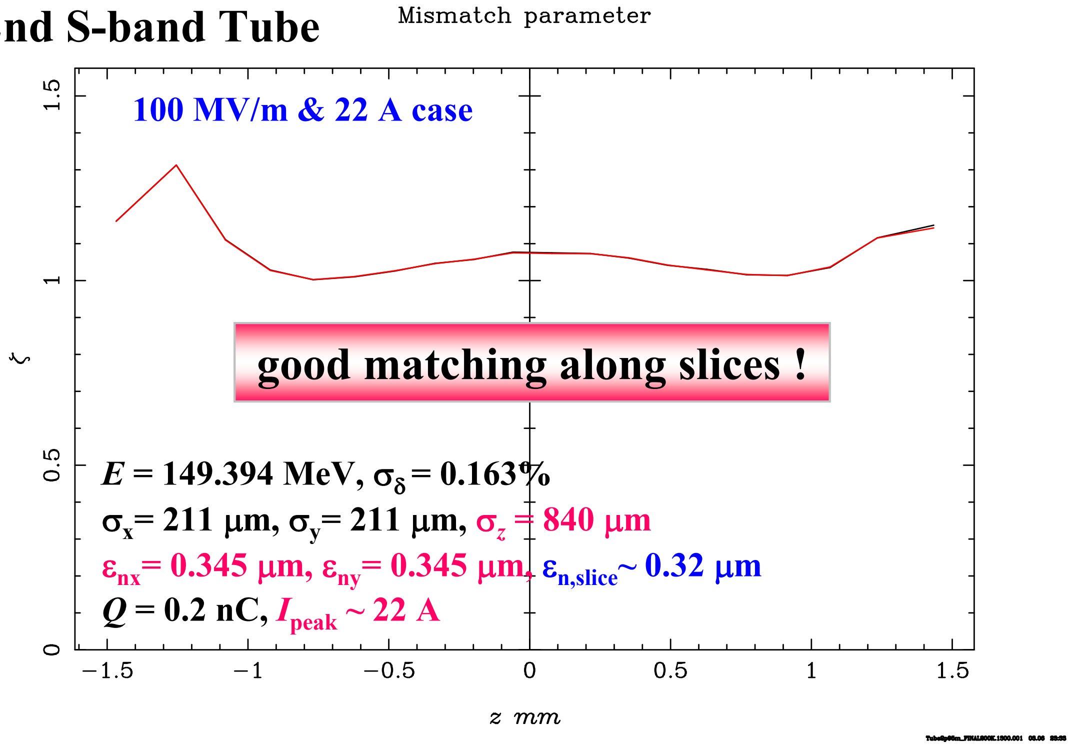
32 A - Project Emittance ~ Slice Emittance
laser $\sigma_{x,y}$ = 270 μm, ΔT = 5.8 ps (FWHM), INSB01@ 2.95 m

22 A - Project Emittance ~ Slice Emittance
laser $\sigma_{x,y}$ = 270 μm, ΔT = 9.9 ps (FWHM), INSB01@ 2.95 m

At the end of the 2nd S-band Tube





$$\varsigma = \frac{1}{2}(\beta_0\gamma - 2\alpha_0\alpha + \gamma_0\beta) \approx 1.0$$

$\alpha_0, \beta_0, \gamma_0$ = Twiss parameters of an integrated bunch

α, β, γ = Twiss parameters of each slice

Optimization-I of 6 GeV PSI-XFEL LINAC

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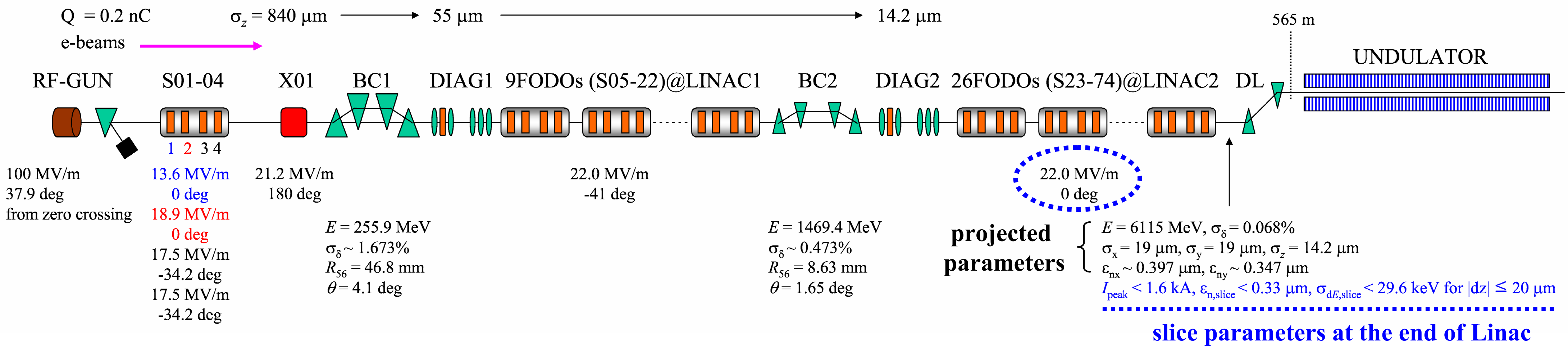
ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space chare, CSR, ISR, and wakefields !



Merits

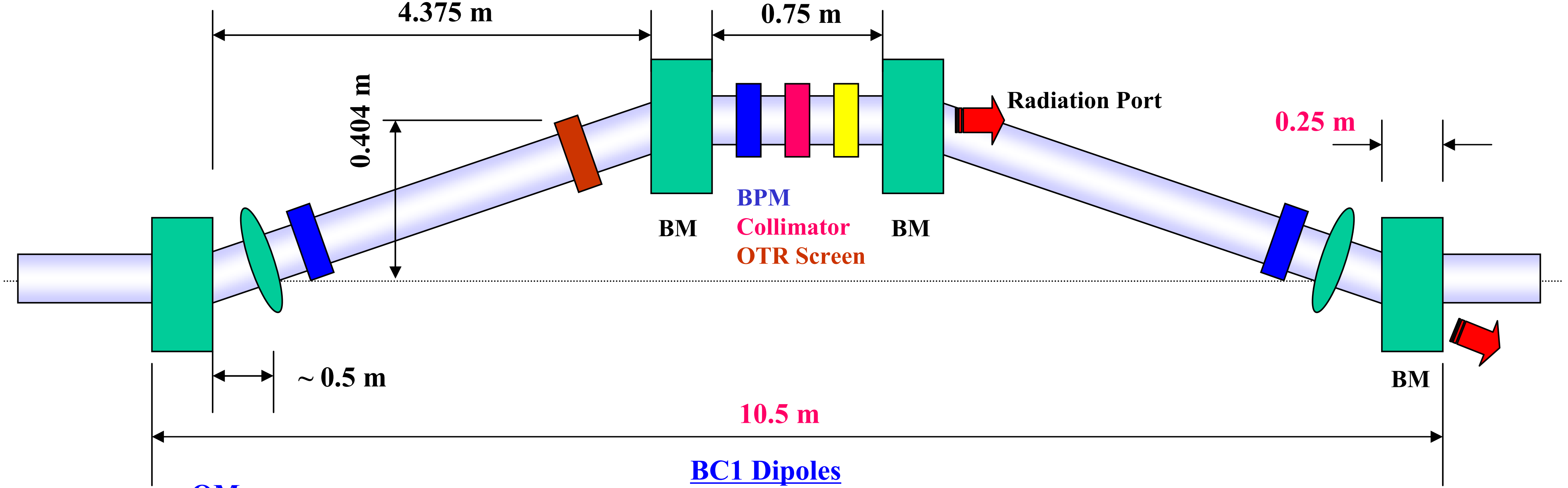
- shortest machine length, z = 565 m† at the undulator entrance
- low projected emittance, $\varepsilon_{nx} \sim 0.40$ μm
- low slice emittance, $\varepsilon_{n,slice} \sim 0.33$ μm
- low rms slice energy spread, $\sigma_{dE,slice} \sim 148$ keV for whole bunch

Demerits

- somewhat long bunch length, $\sigma_z = 14.2$ μm and somewhat low peak current, $I_{peak} \sim 1.6$ kA
- high relative rms projected energy spread, $\sigma_\delta \sim 0.068\%$
- linear but large energy chirping

† : z = 565 m is the minimum length for 6 GeV Linac, Dog-Leg (DL), DIAG3 in DL, and Switch Yards in LINAC2

Optimization-I BC1

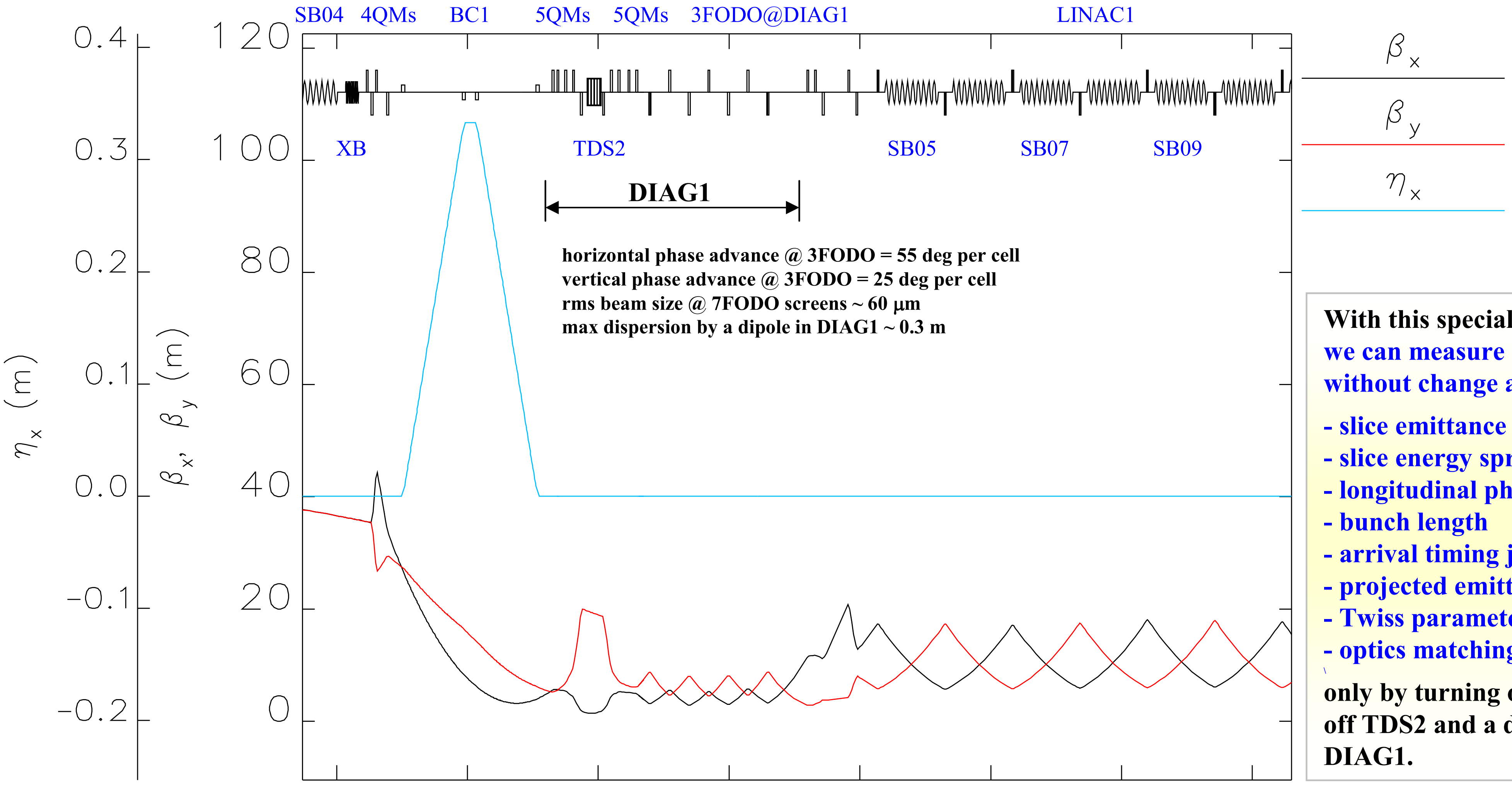


QMs
length ~ 0.1 m
max gradient ~ 1.5 T/m

BC1 Dipoles
length = 0.25 m
max bending angle ~ 5 deg @ 250 MeV

E = 255.9 MeV
$\sigma_\delta \sim$ 1.673%
R_{56} = 46.8 mm
θ = 4.1 deg

Optimization-I Optics around BC1 & DIAG1



With this special DIAG1, we can measure followings without change any optics:

- slice emittance
- slice energy spread
- longitudinal phase space
- bunch length
- arrival timing jitter
- projected emittance
- Twiss parameters
- optics matching

only by turning on and/or off TDS2 and a dipole in DIAG1.

$$\frac{\varepsilon}{\varepsilon_0} \approx \sqrt{1+\frac{(0.22)^2}{36}\frac{r_e^2 N^2}{\gamma\varepsilon_N\beta}\left(\frac{|\theta|^5 L_B}{\sigma_z^4}\right)^{2/3}\left[L_B^2\left(1+\alpha^2\right)+9\beta^2+6\alpha\beta L_B\right]}$$

Lattice optimization to minimize this term

Optimization-I Performance of BC1

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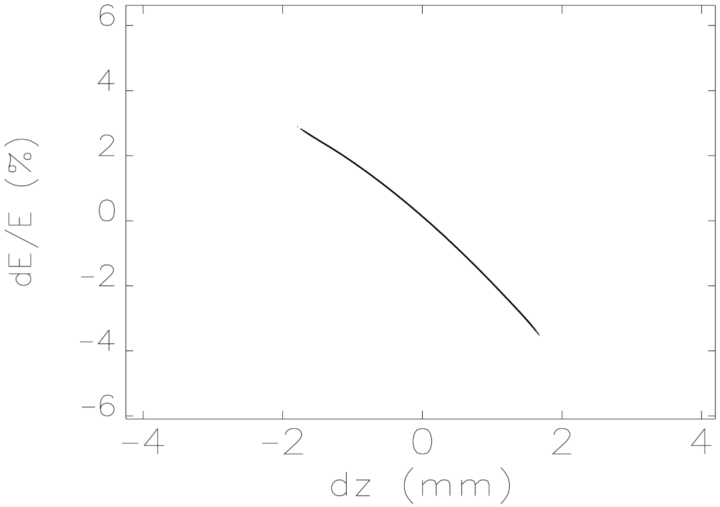
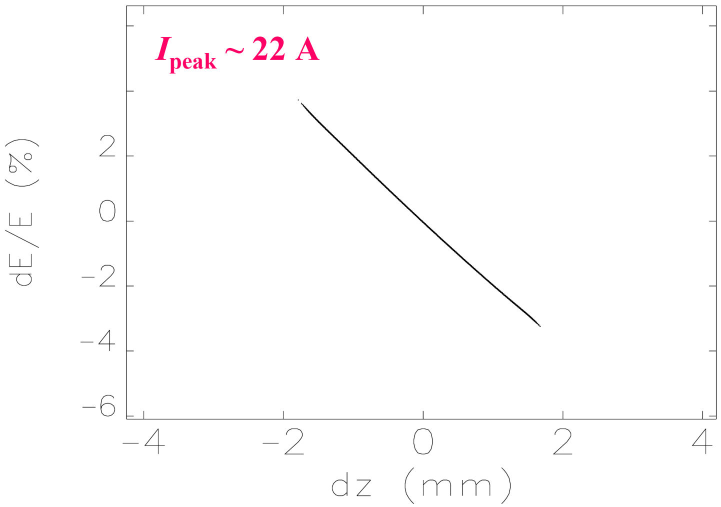


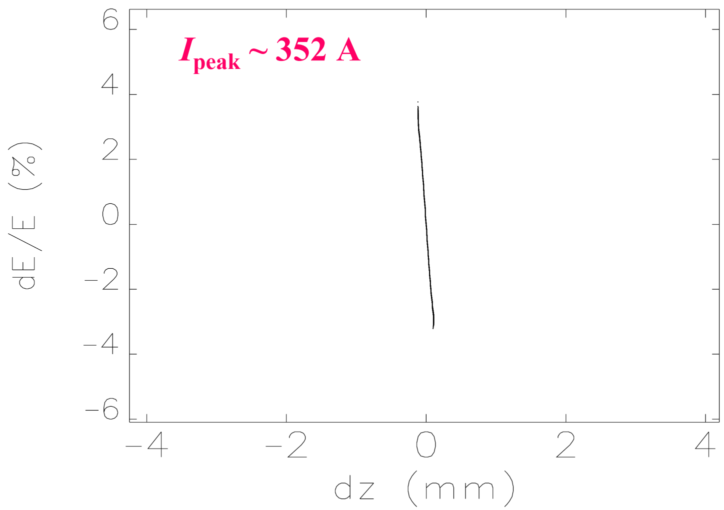
Before X01

E ~ 256 MeV, Q = 0.2 nC
σ_δ ~ 1.67%, σ_z = 840 μm
ε_{nx} ~ 0.35 μm, ε_{ny} ~ 0.35 μm



Before BC1

E ~ 256 MeV, Q = 0.2 nC
σ_δ ~ 1.67%, σ_z = 58 μm
ε_{nx} ~ 0.38 μm, ε_{ny} ~ 0.35 μm



After BC1

Optimization-I Performance of BC1

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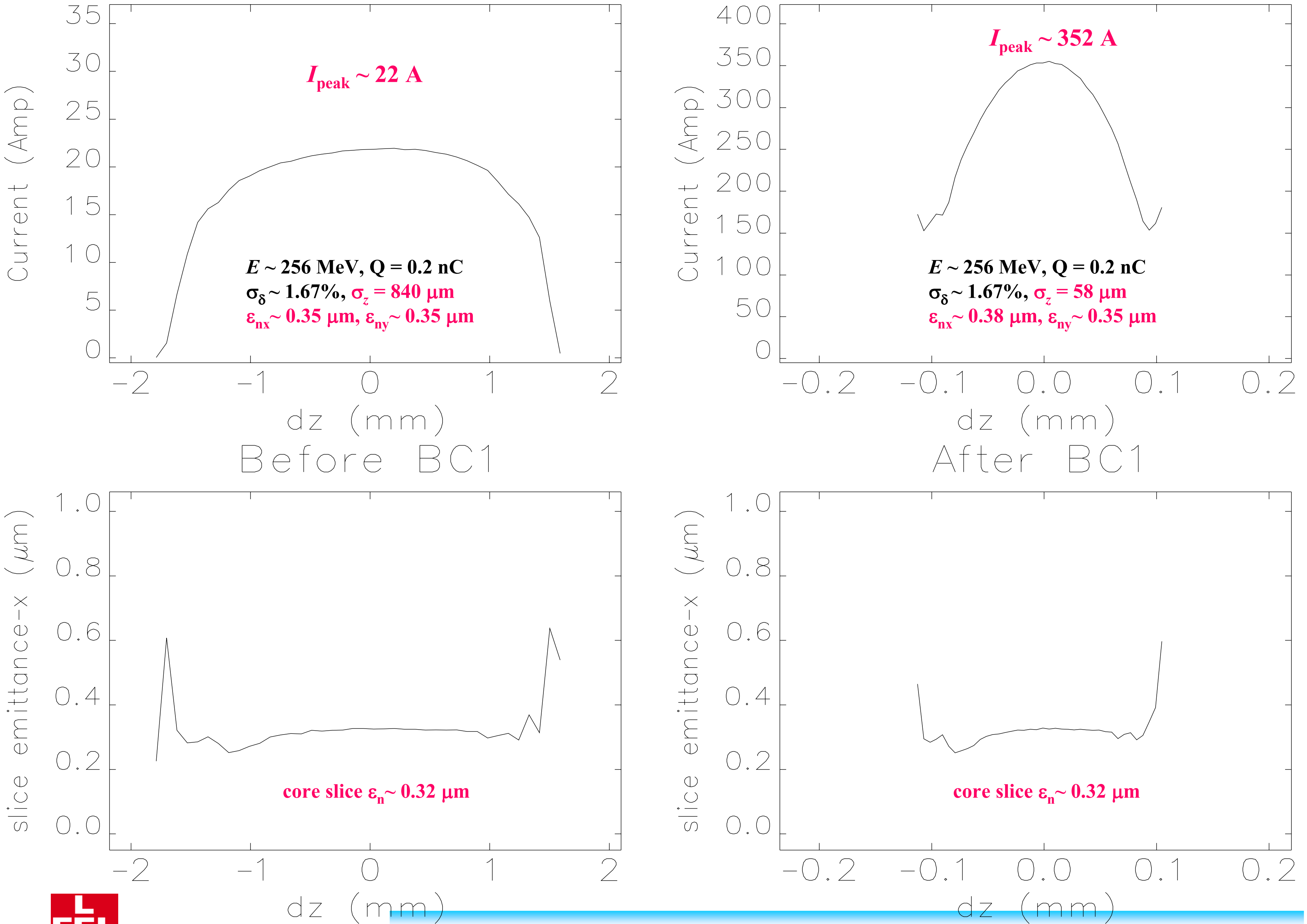

DIAG1 Optics for TDS2 Operation

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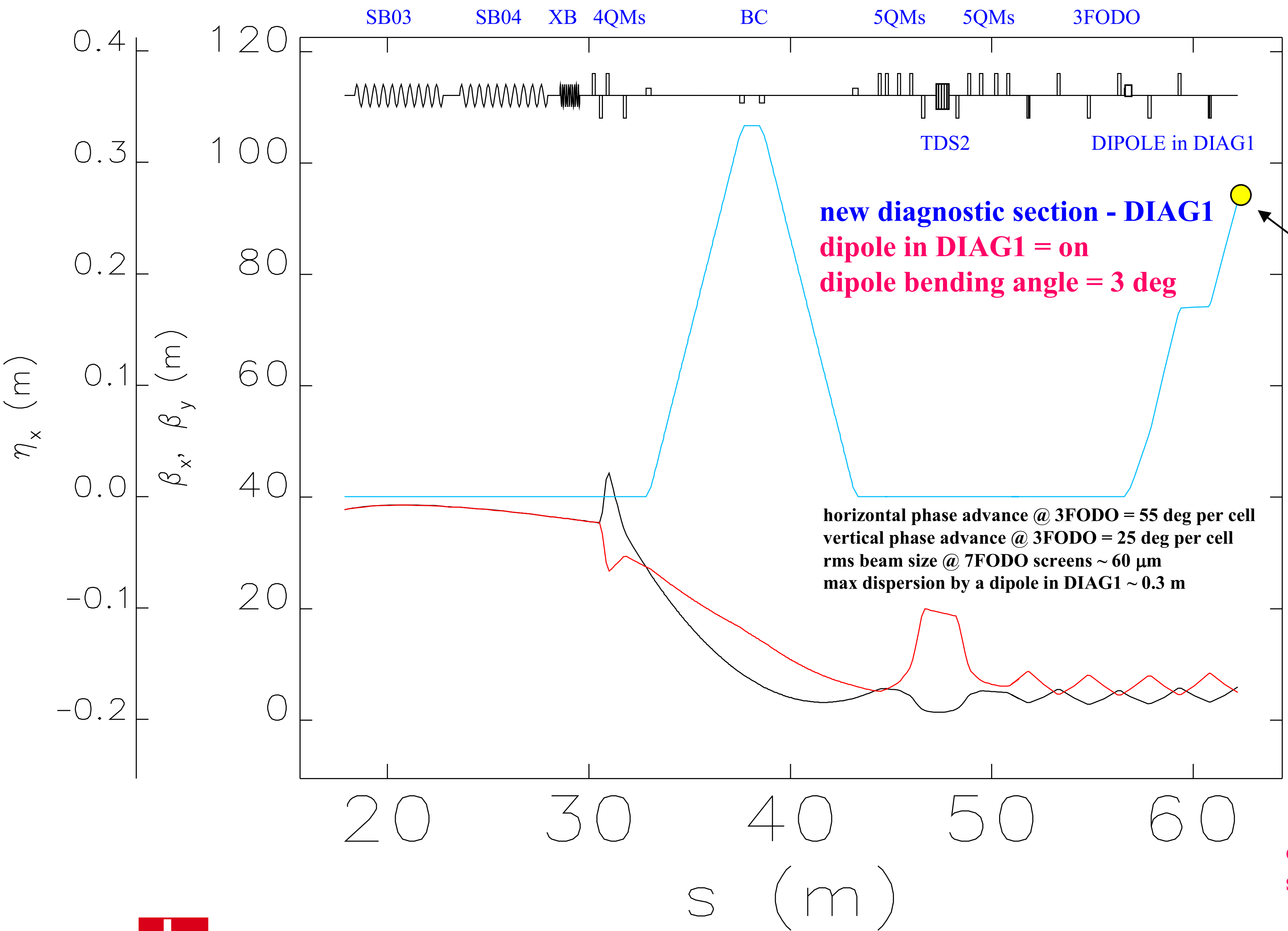
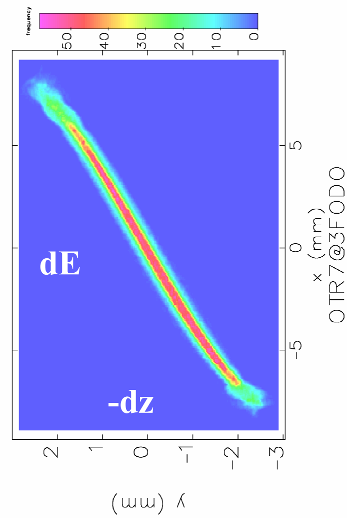
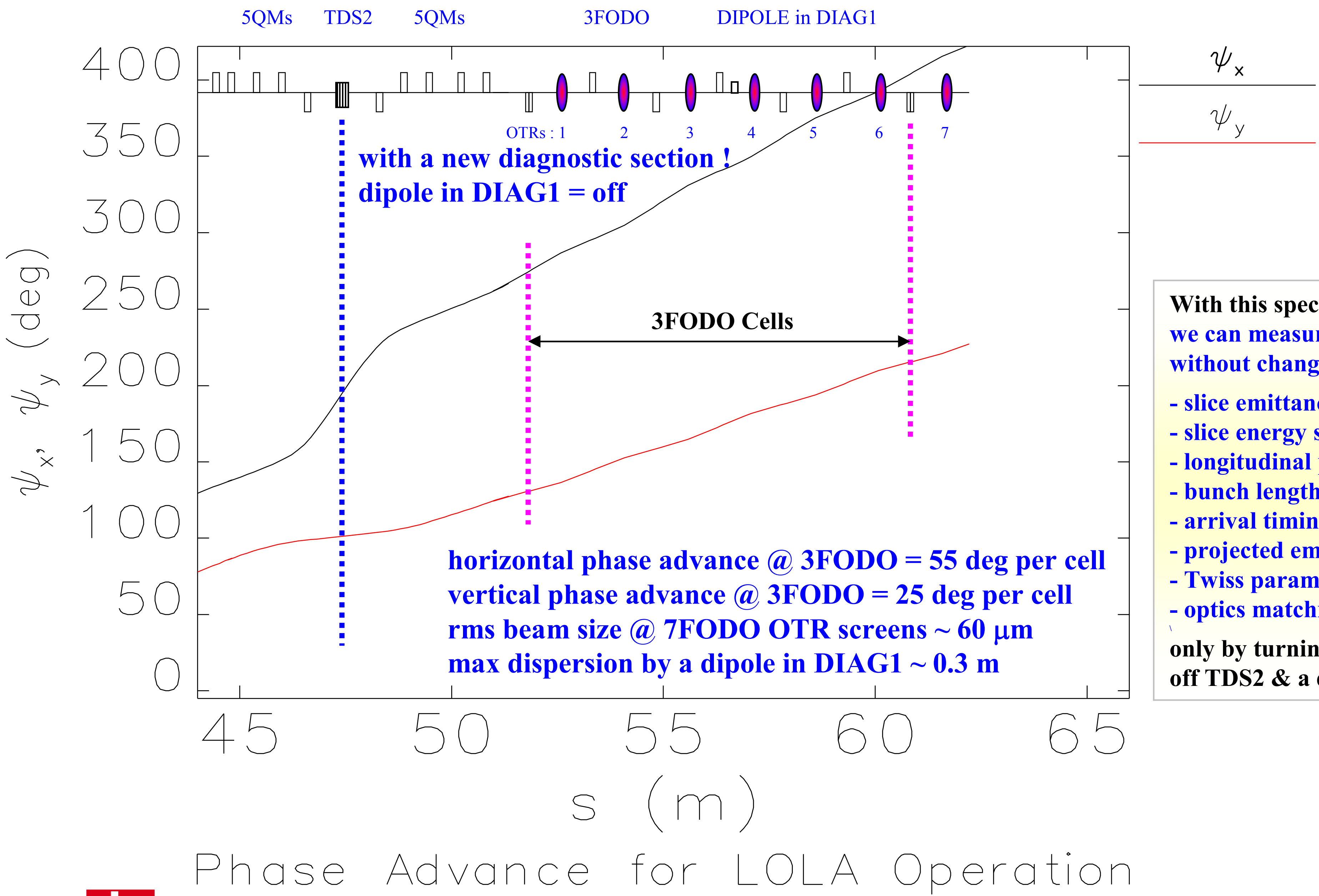


ELEGANT simulation on the reconstruction of the longitudinal phase space by the TDS2 cavity, on a last OTR at DIAG1 region



compare longitudinal phase space (After BC1) in page 10

Phase Advance along 7OTRs in DIAG1

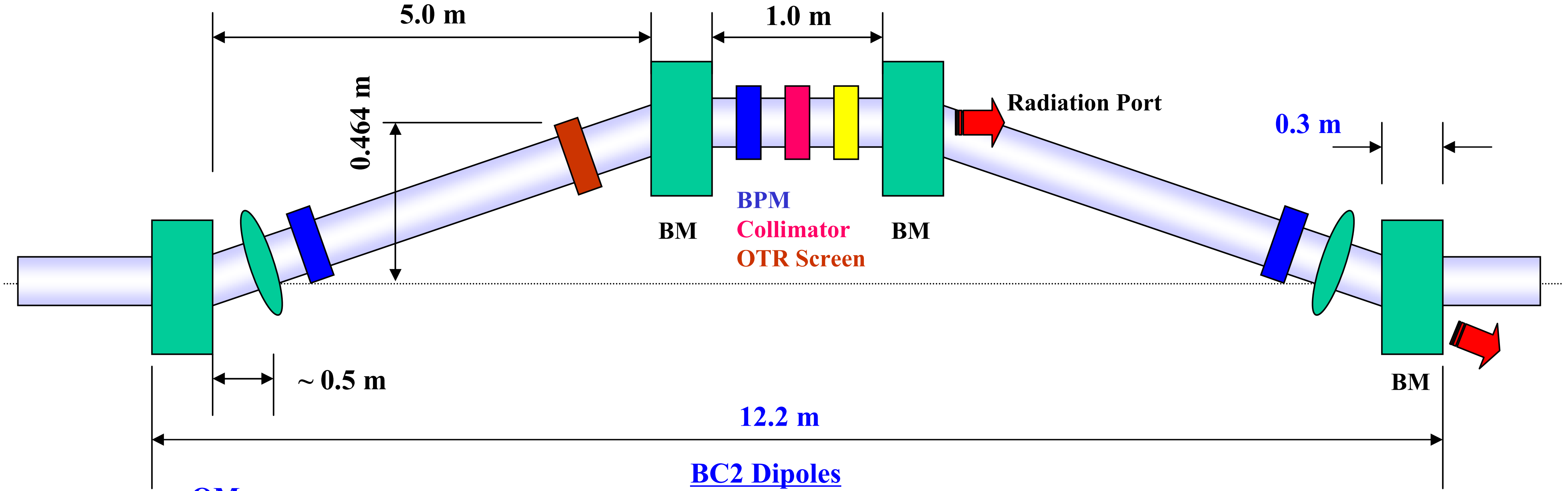


With this special DIAG1,
we can measure followings without change any optics:

- slice emittance
- slice energy spread
- longitudinal phase space
- bunch length
- arrival timing jitter
- projected emittance
- Twiss parameters
- optics matching

only by turning on and/or off TDS2 & a dipole in DIAG2.

Optimization-I BC2 Layout



QMs
length ~ 0.1 m
max gradient ~ 9.0 T/m

BC2 Dipoles
length = 0.30 m
max bending angle @ 1.5 GeV ~ 5 deg

E = 1469.4 MeV
σ_δ ~ 0.473%
R_{56} = 8.63 mm
θ = 1.65 deg

Optimization-I Optics around BC2 & DIAG2

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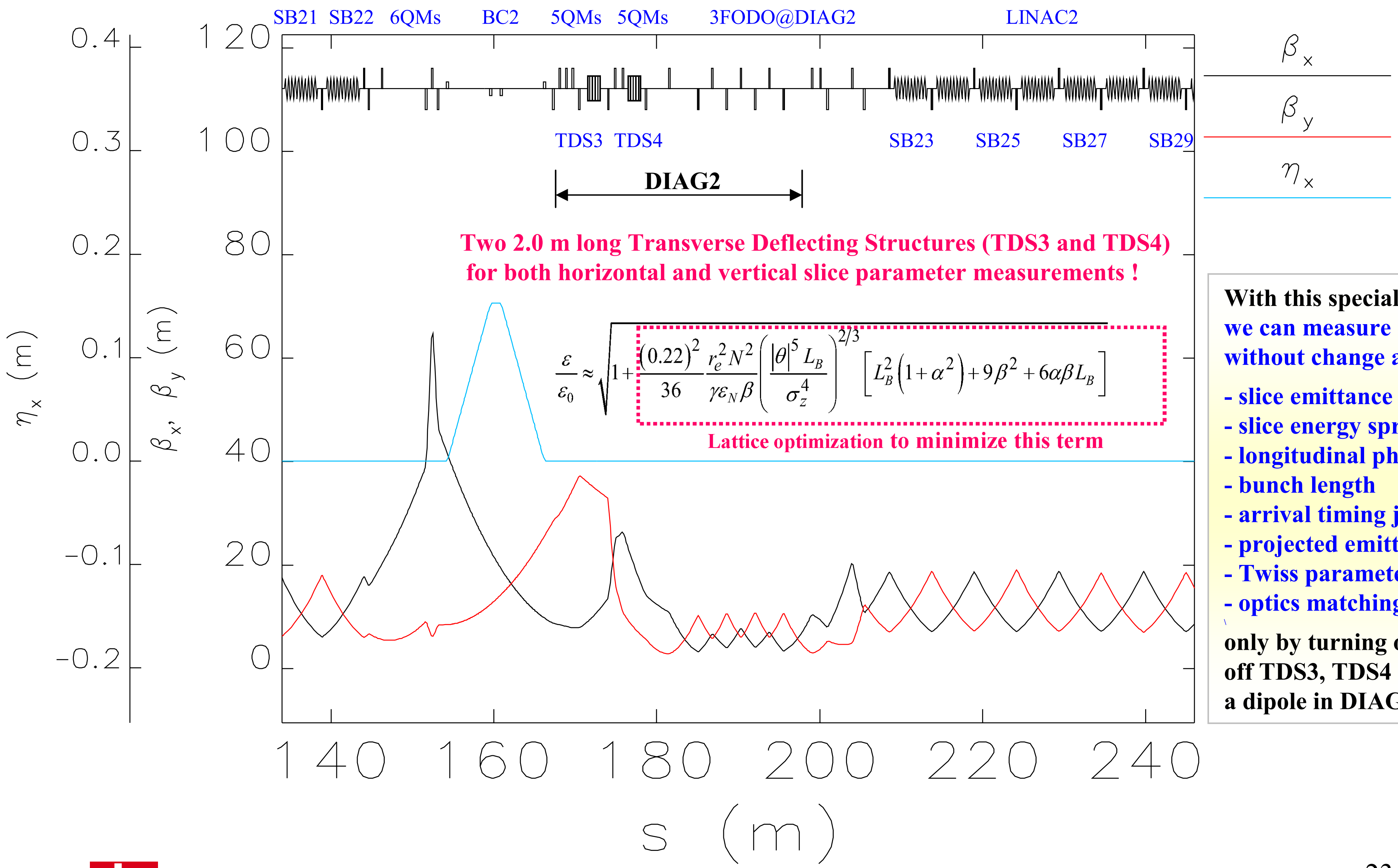
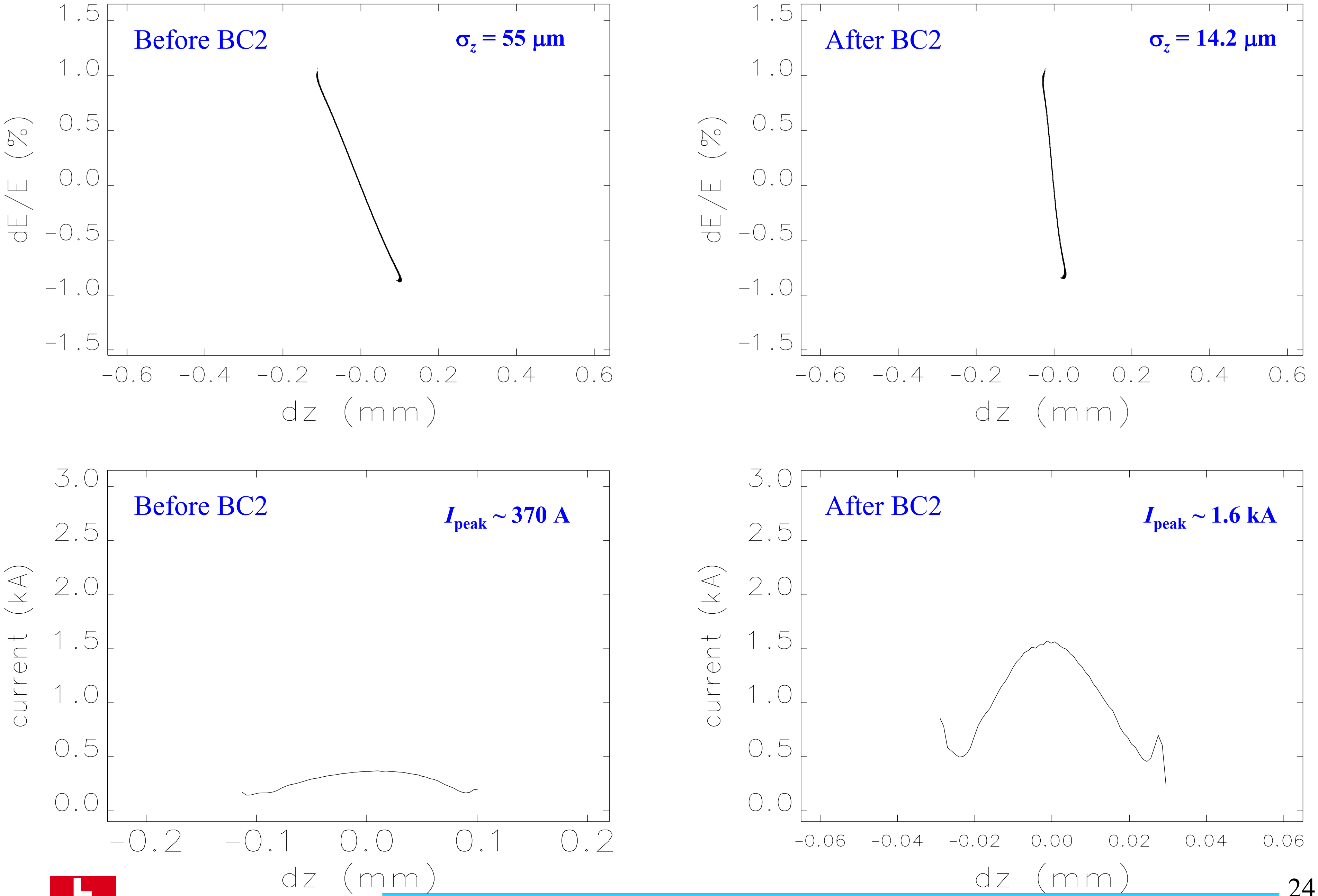


With this special DIAG2,
we can measure followings without change any optics:

- **slice emittance**
- **slice energy spread**
- **longitudinal phase space**
- **bunch length**
- **arrival timing jitter**
- **projected emittance**
- **Twiss parameters**
- **optics matching**

only by turning on and/or off TDS3, TDS4 and a dipole in DIAG2.

Optimization-I Performance of BC2



Optimization-I Performance of BC2

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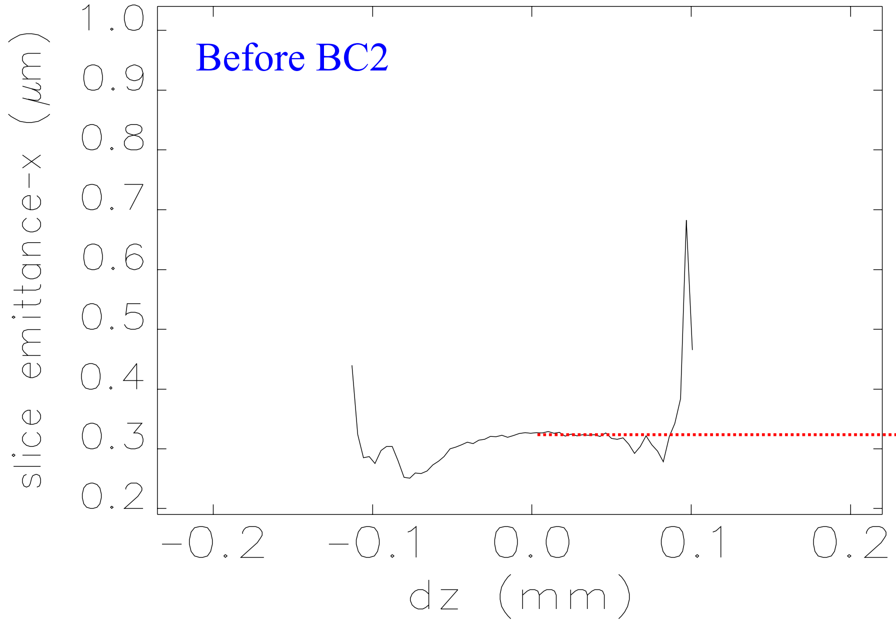
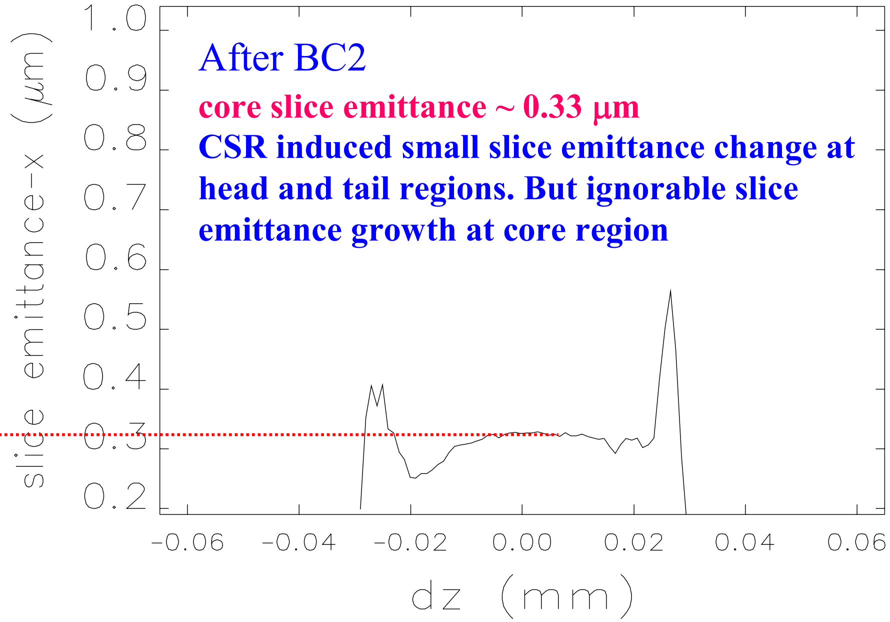
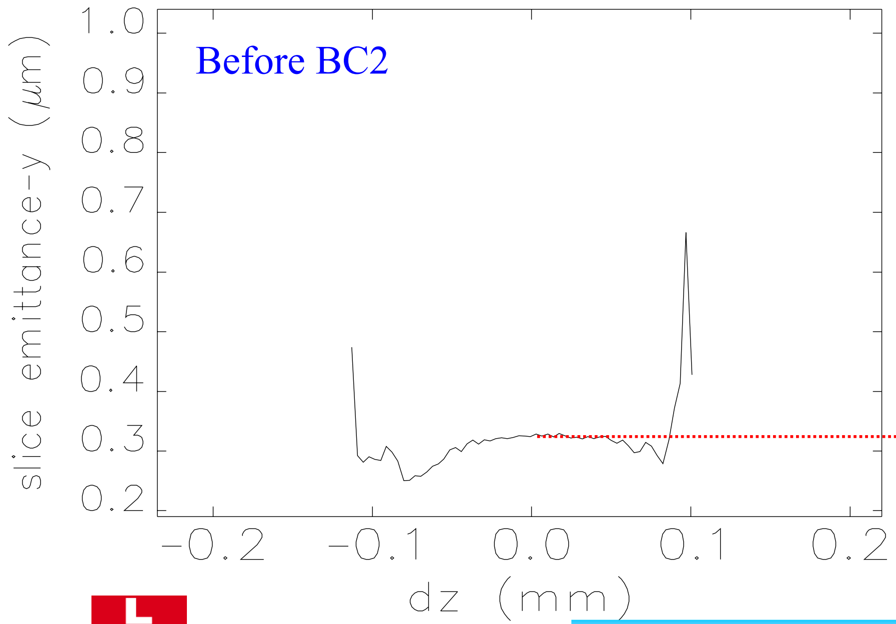
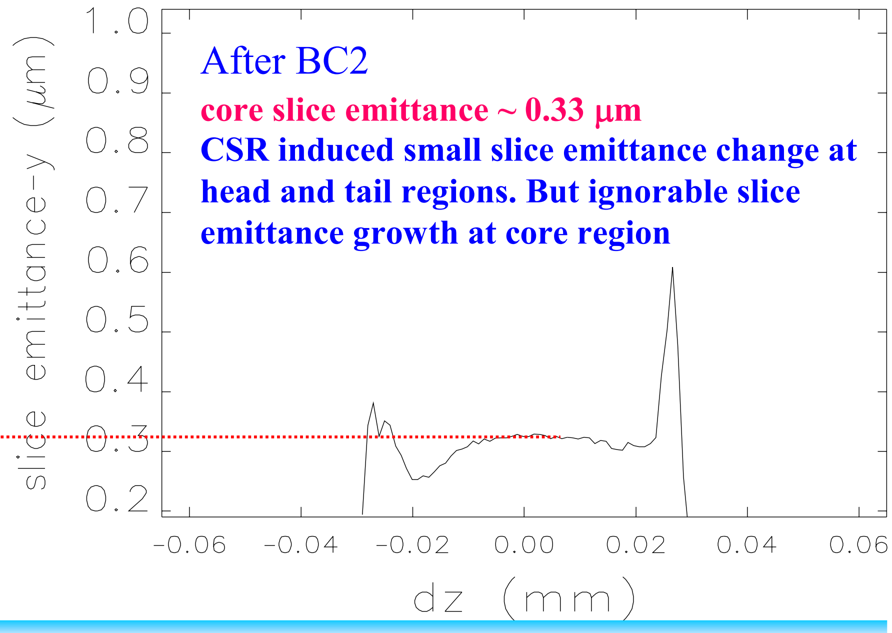
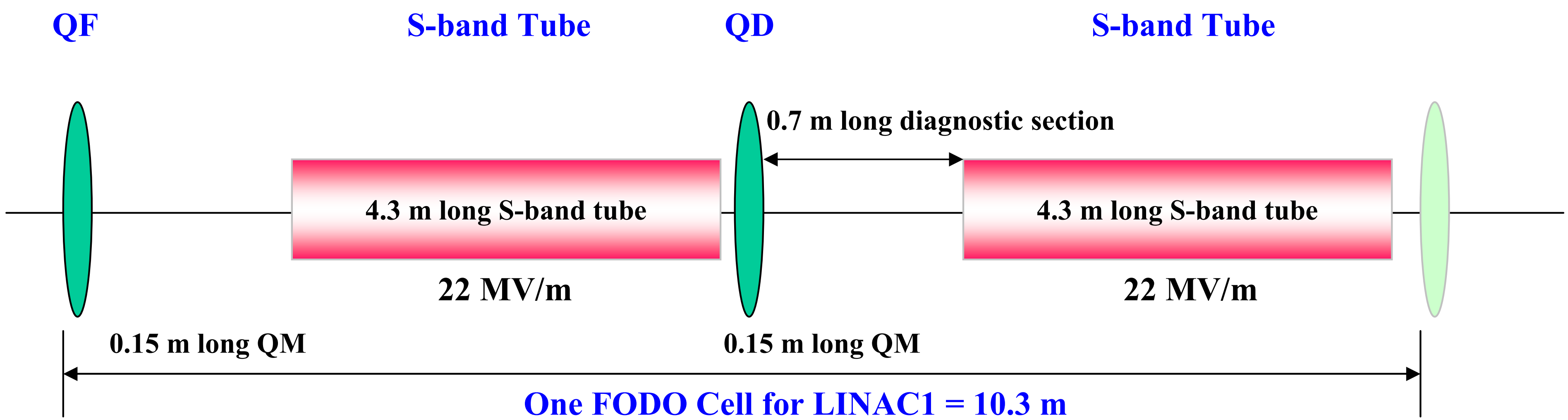








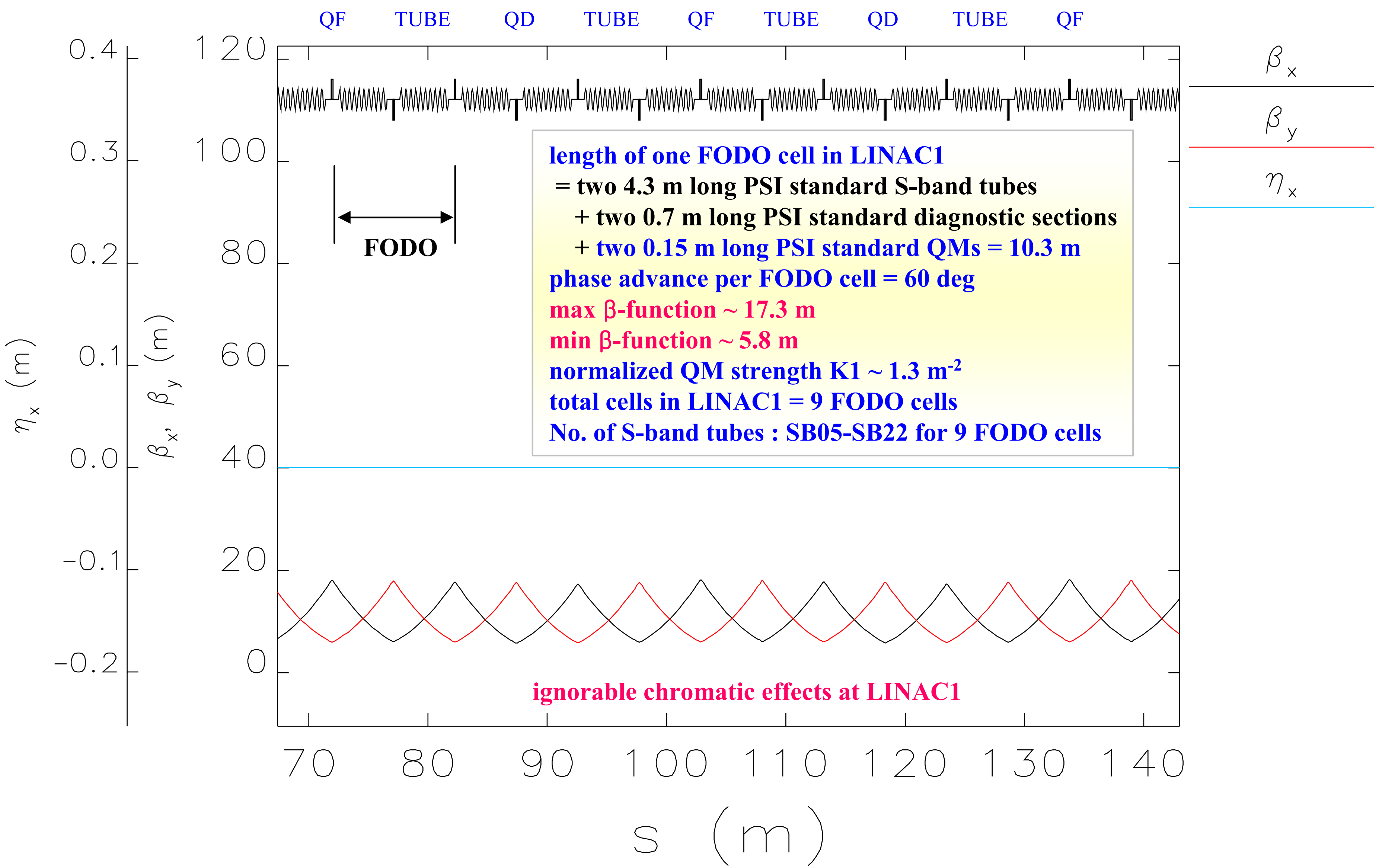
Optimization-I LINAC1 between BC1 & BC2



length of one FODO cell in LINAC1
= two 4.3 m long PSI standard S-band tubes
+ two 0.7 m long PSI standard diagnostic sections
+ two 0.15 m long PSI standard QMs = 10.3 m

phase advance per FODO cell = 60 deg
max β-function ~ 17.3 m
min β-function ~ 5.8 m
normalized QM strength K1 ~ 1.3 m^{-2}
QM gradient @ 1.5 GeV ~ 6.5 T/m
total cells in LINAC1 = 9 FODO cells
No. of S-band tubes = SB05-SB22 for 9 FODO cells
total needed S-band tubes = 18 tubes

Optimization-I LINAC1 between BC1 & BC2



Optimization-I LINAC2 between BC2 & DL

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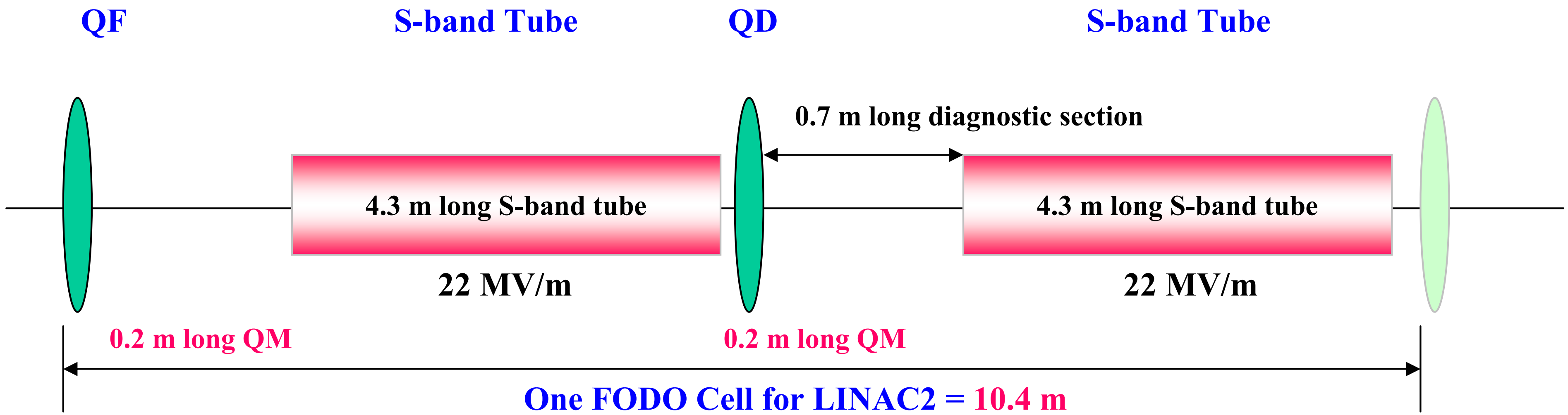

length of one FODO cell in LINAC2
= two 4.3 m long PSI standard S-band tubes
+ two 0.7 m long PSI standard diagnostic sections
+ two 0.2 m long QMs = 10.4 m
phase advance per FODO cell = 60 deg
max β-function ~ 18.8 m
min β-function ~ 7.2 m
normalized QM strength K1 ~ 0.87 m^{-2}
QM gradient @ 8 GeV = 23.2 T/m
total cells in LINAC2 = 26 FODO cells
No. of S-band tubes = SB23-SB74 for 26 FODO cells
total needed S-band tubes = 52 tubes for Optimization-I (270.4 m long)
= 68 tubes for Optimization-III or V (353.6 m long)

Optimization-I LINAC2 between BC2 & DL

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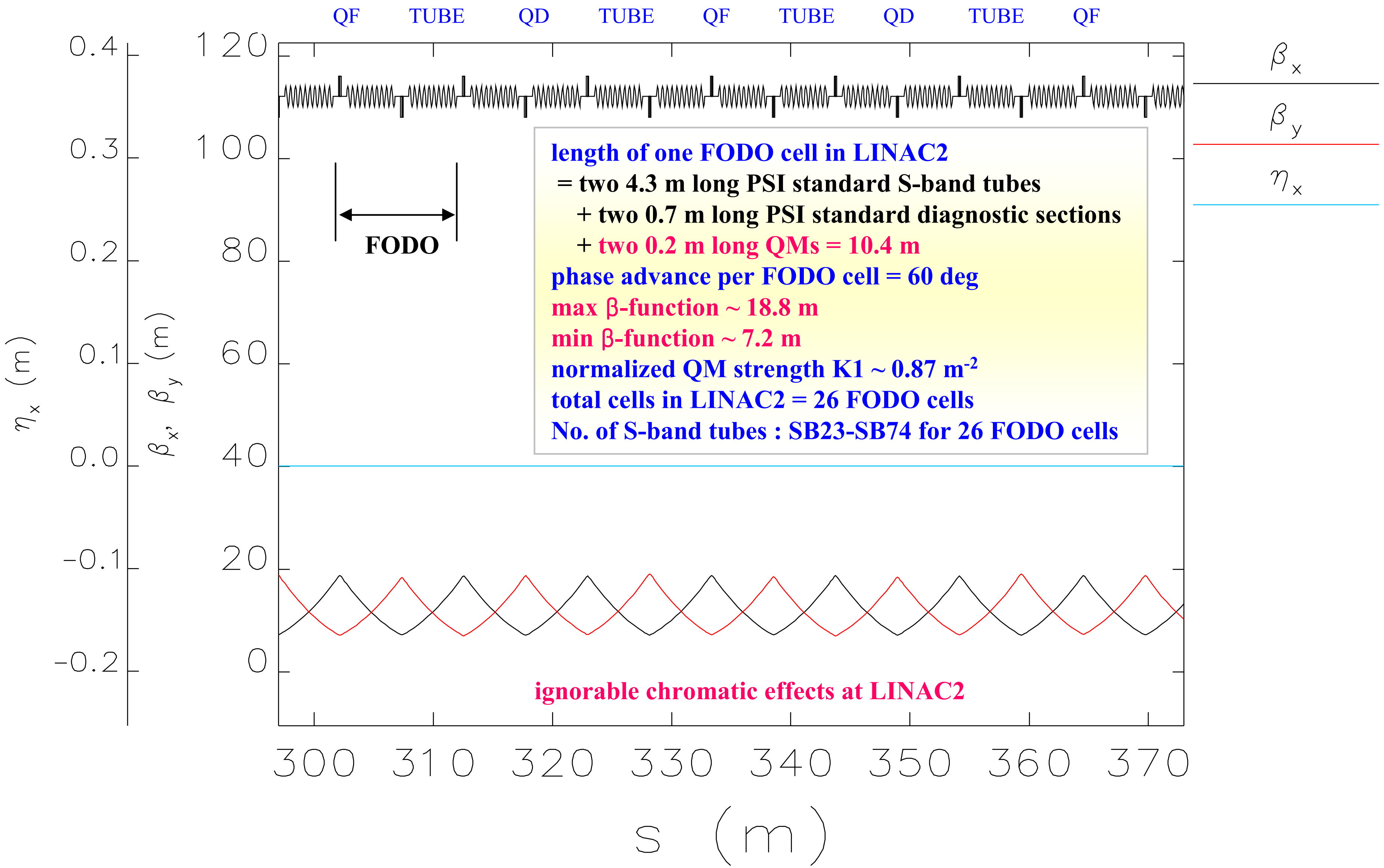
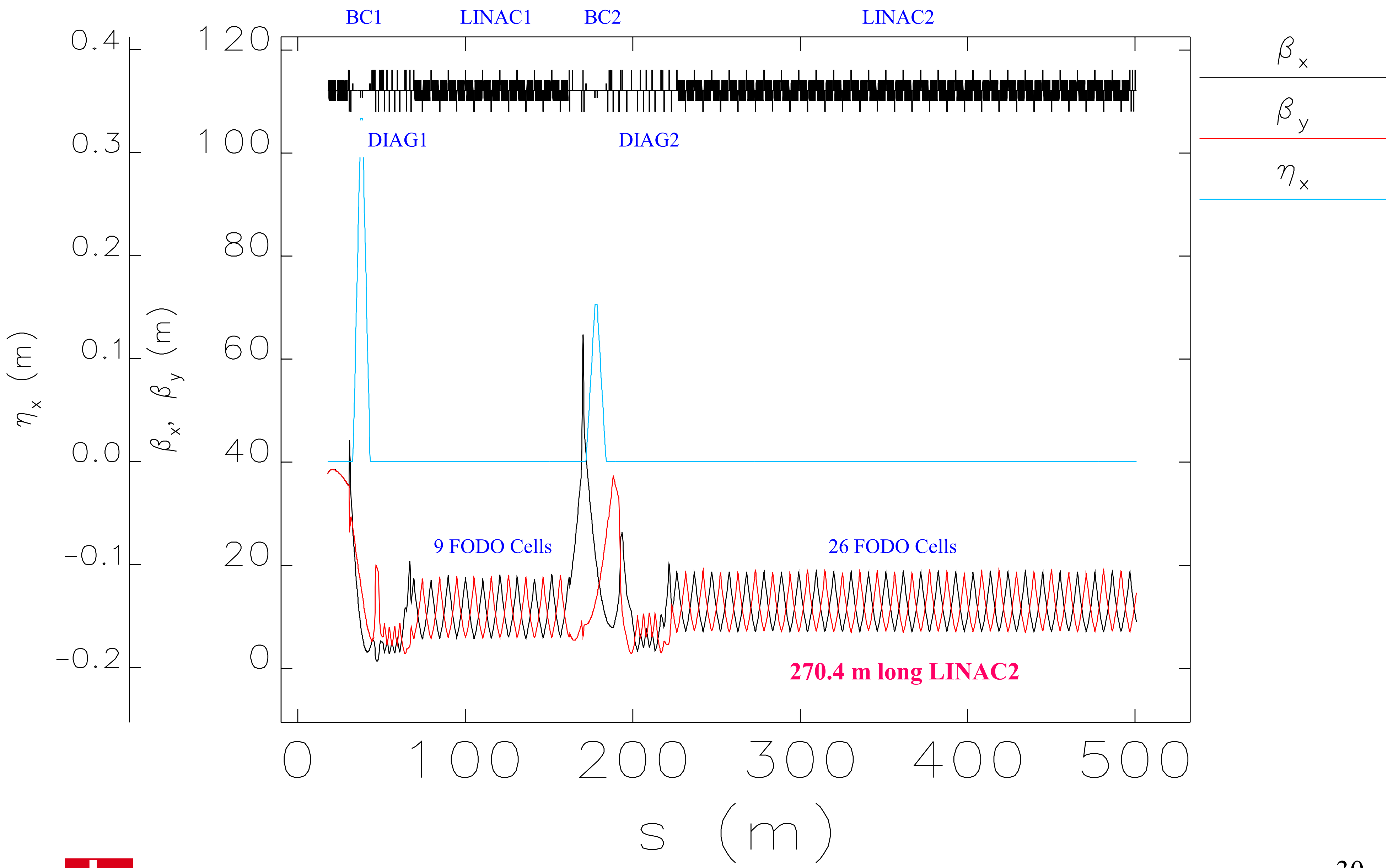
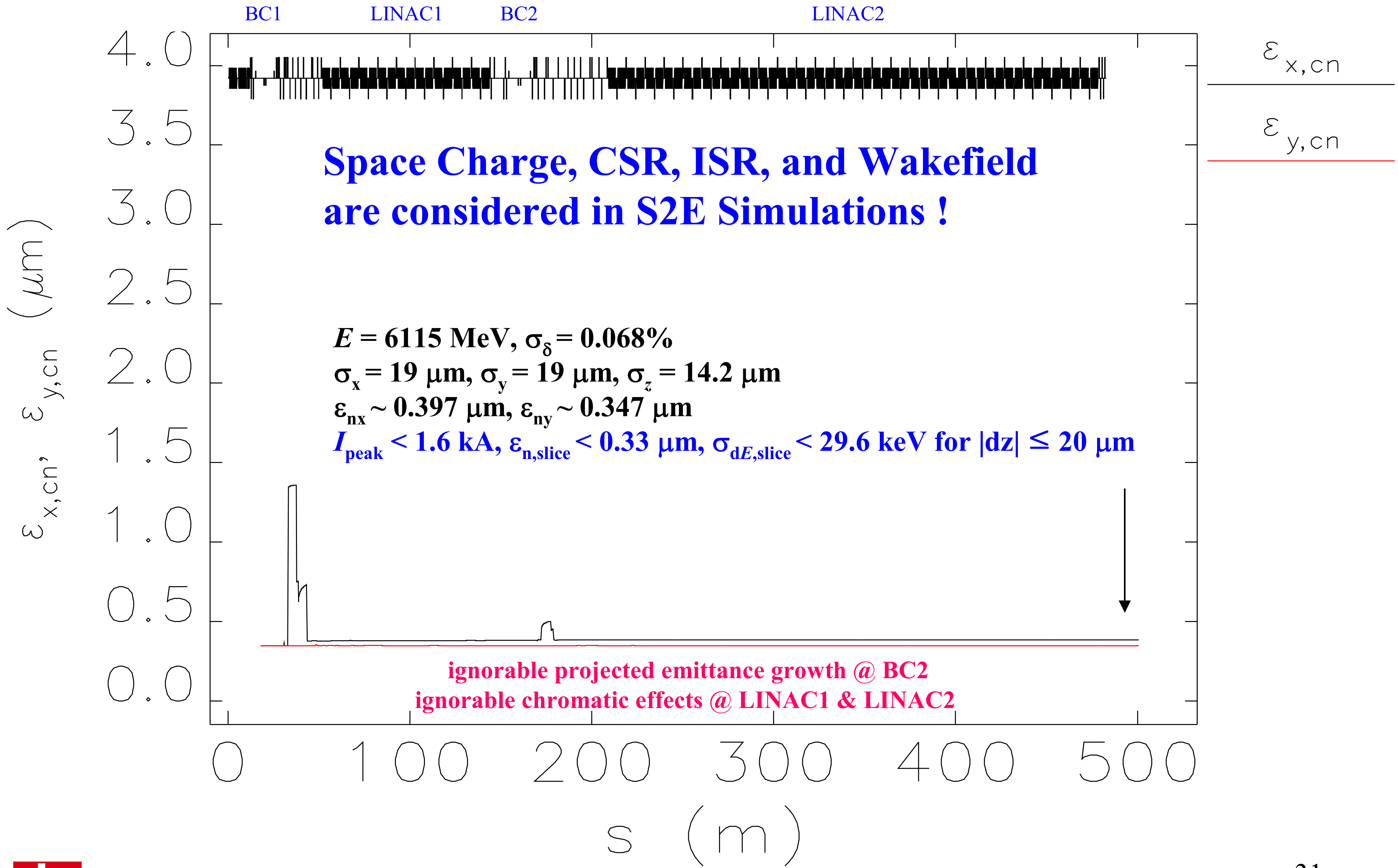


Optimization-I Optics of 6 GeV LINAC

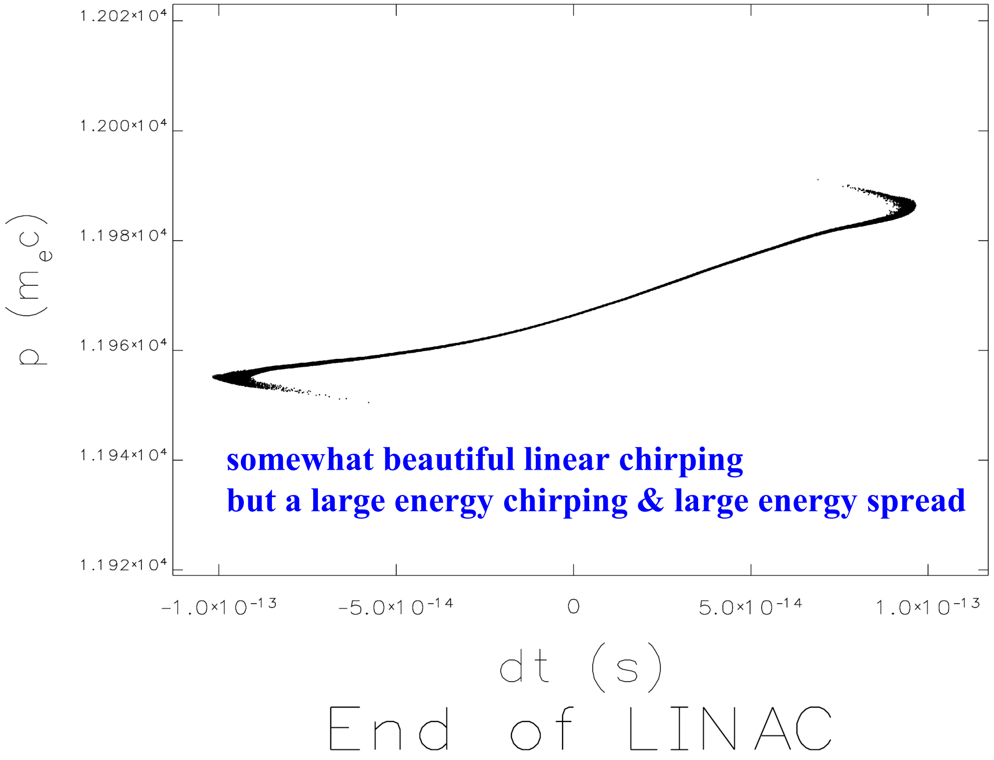


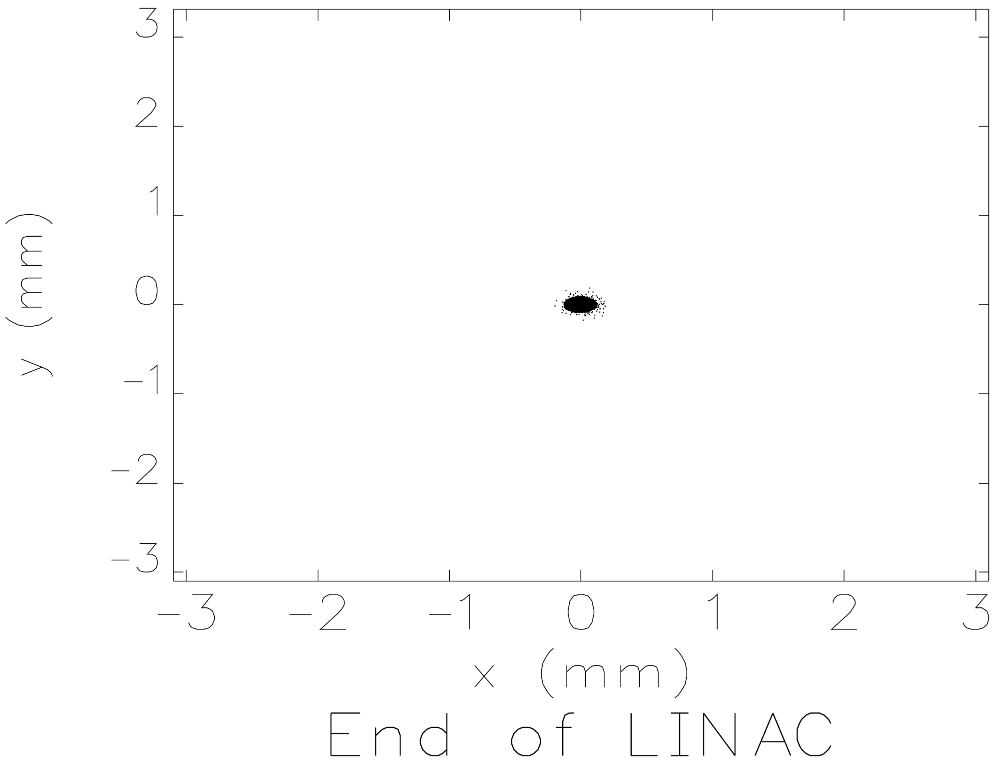
Optimization-I Projected Emittance

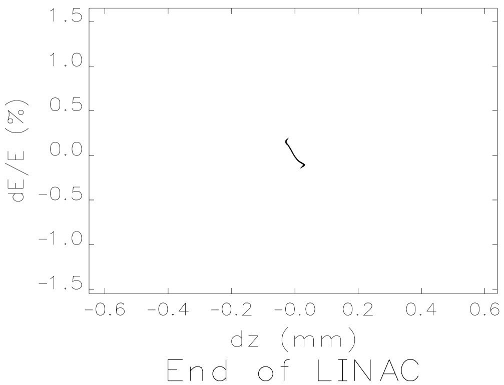
PAUL SCHERRER INSTITUT



Optimization-I Phase Spaces at 6 GeV







E = 6115 MeV, σ_δ = 0.068%

σ_x = 19 μm, σ_y = 19 μm, σ_z = 14.2 μm

ε_{nx} ~ 0.397 μm, ε_{ny} ~ 0.347 μm

I_{peak} < 1.6 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 29.6 keV for |dz| ≤ 20 μm

Optimization-I Slice Parameters at 6 GeV

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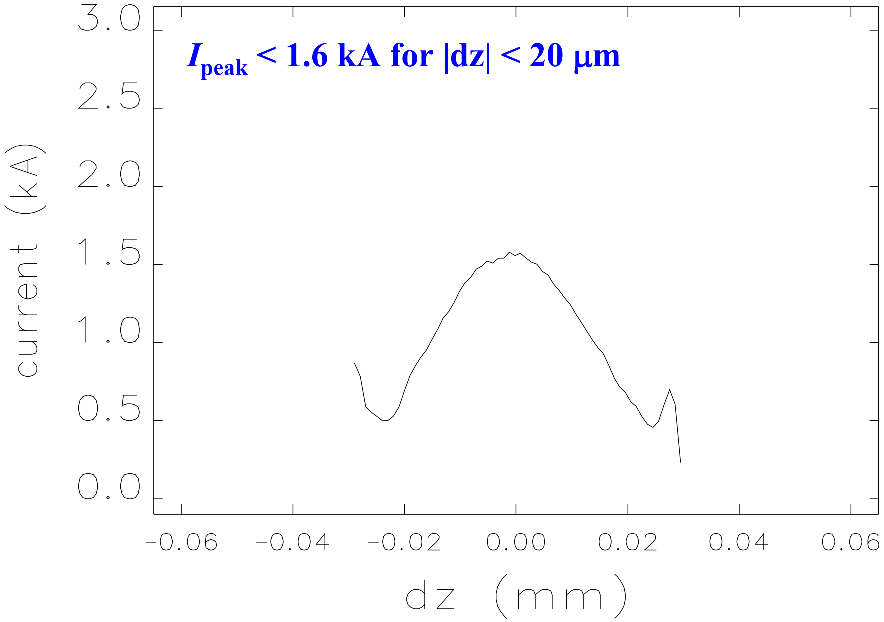
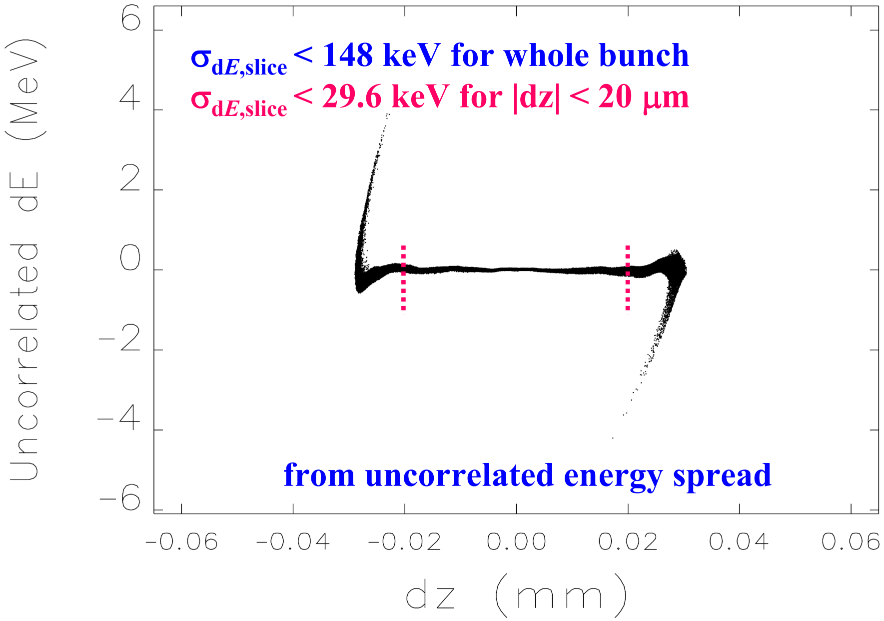
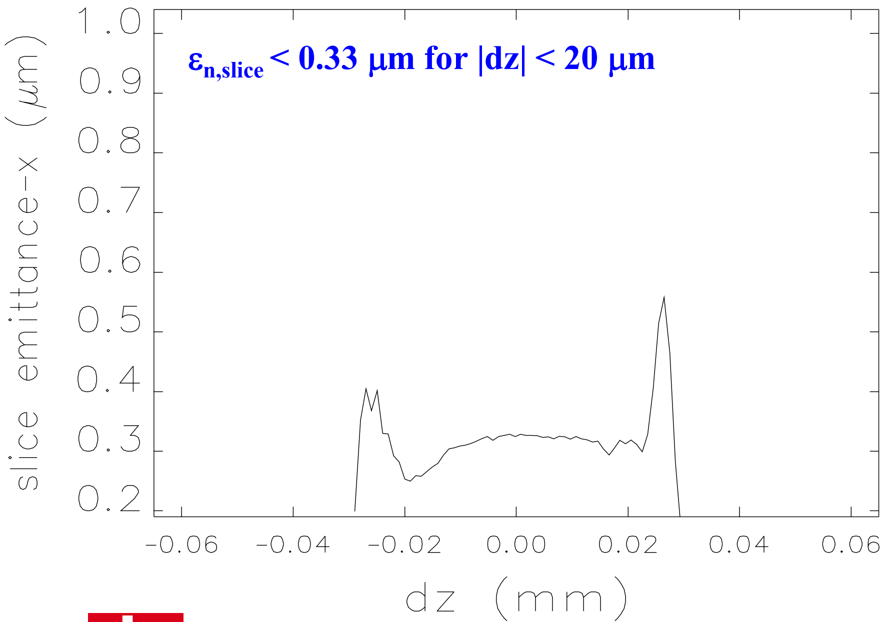
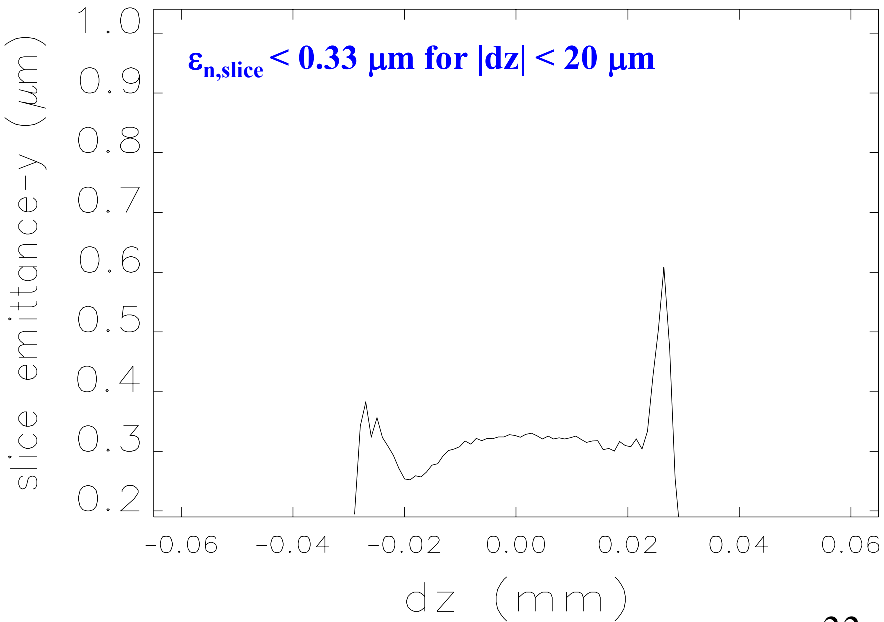




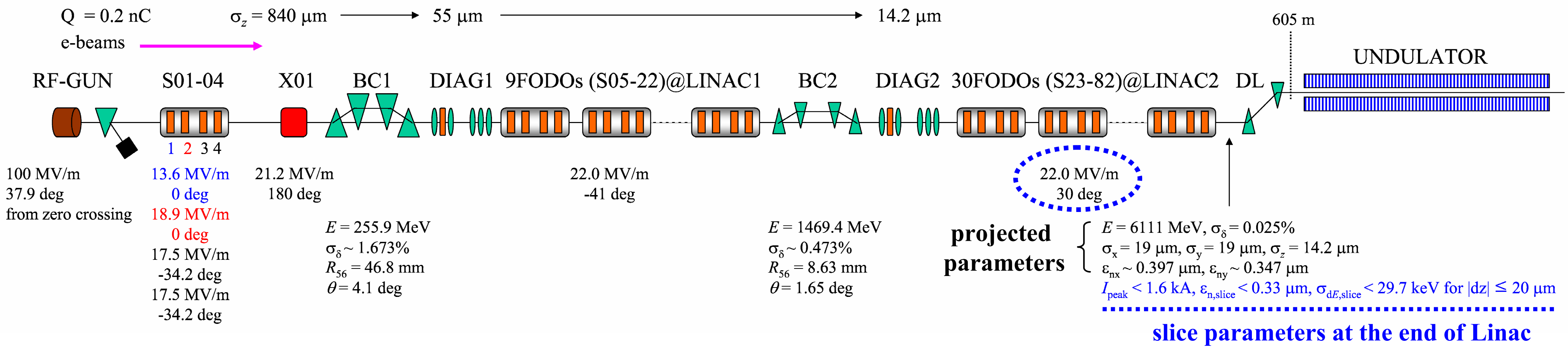




Optimization-II of 6 GeV PSI-XFEL LINAC

PAUL SCHERRER INSTITUT

ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space chare, CSR, ISR, and wakefields !



Merits

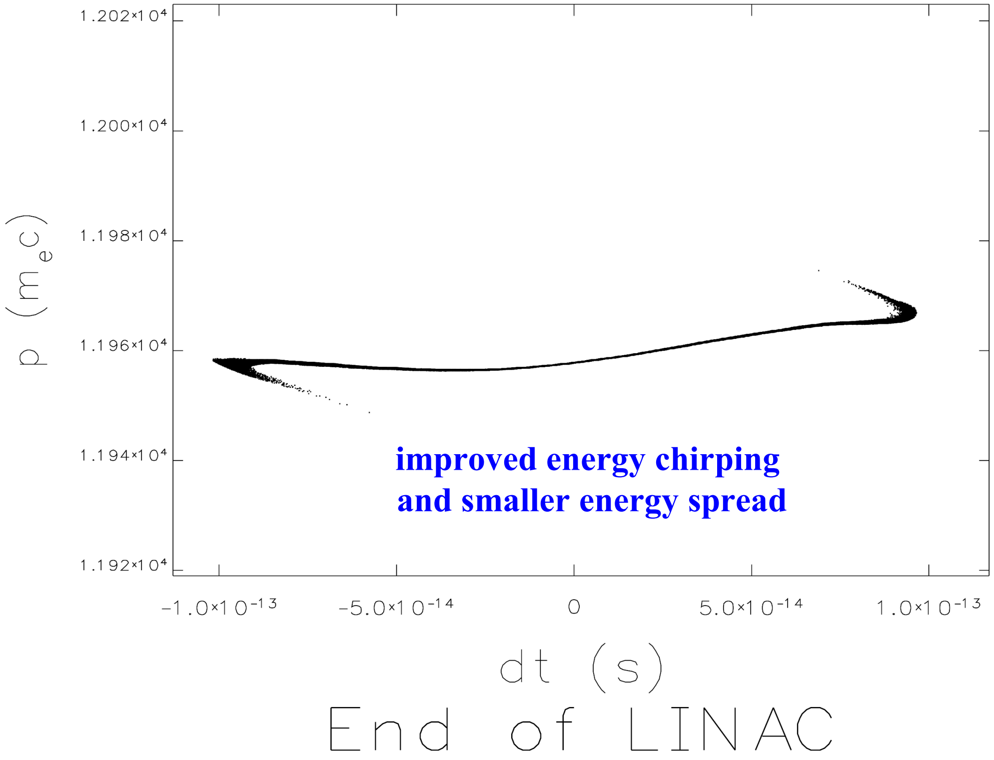
- improved relative rms projected energy spread, $\sigma_\delta \sim 0.025\%$
- low projected emittance, $\varepsilon_{nx} \sim 0.40$ μm
- low slice emittance, $\varepsilon_{n,slice} \sim 0.33$ μm
- low rms slice energy spread, $\sigma_{dE,slice} \sim 148$ keV for whole bunch
- improved energy chirping

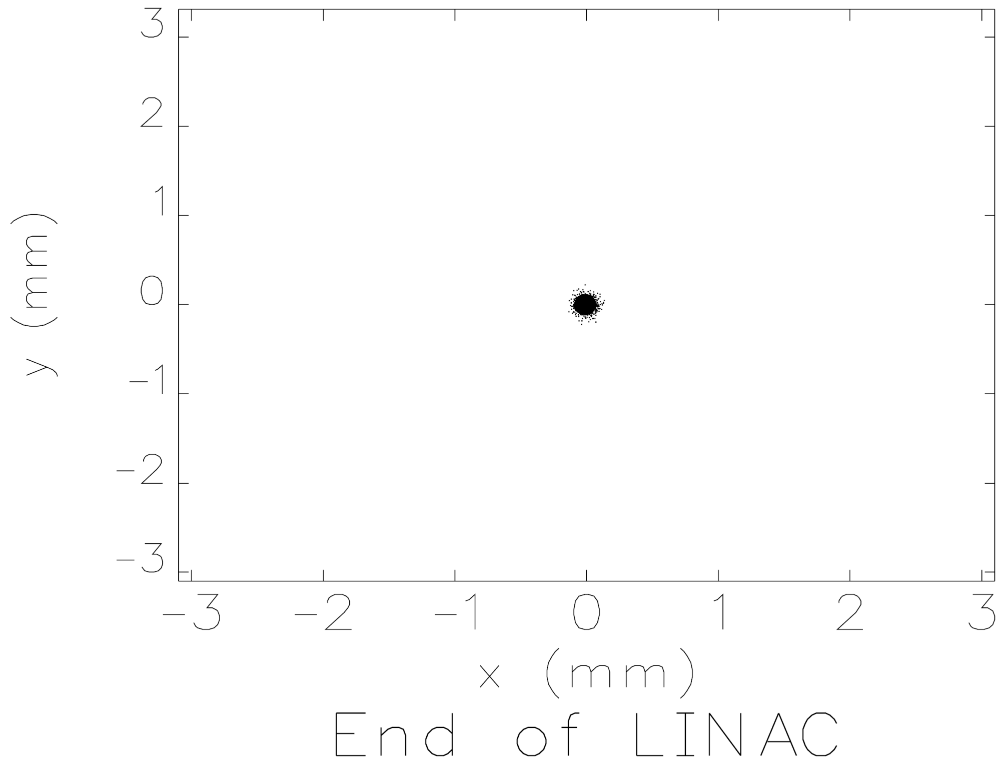
Demerits

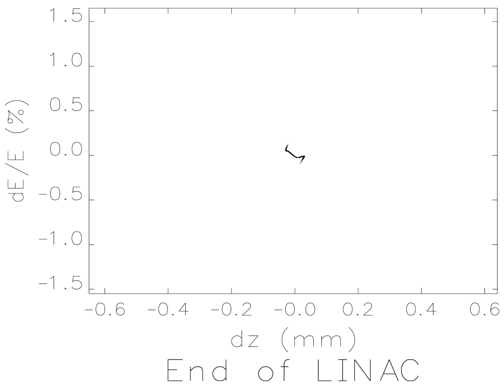
- somewhat long bunch length, $\sigma_z = 14.2$ μm and somewhat low peak current, $I_{peak} \sim 1.6$ kA
- somewhat longer machine length, z = 605 m† at the undulator entrance

† : z = 605 m is the minimum length for 6 GeV Linac, Dog-Leg (DL), DIAG3 in DL, and Switch Yards in LINAC2

Optimization-II Phase Spaces at 6 GeV







E = 6111 MeV, σ_δ = 0.025%

σ_x = 19 μm, σ_y = 19 μm, σ_z = 14.2 μm

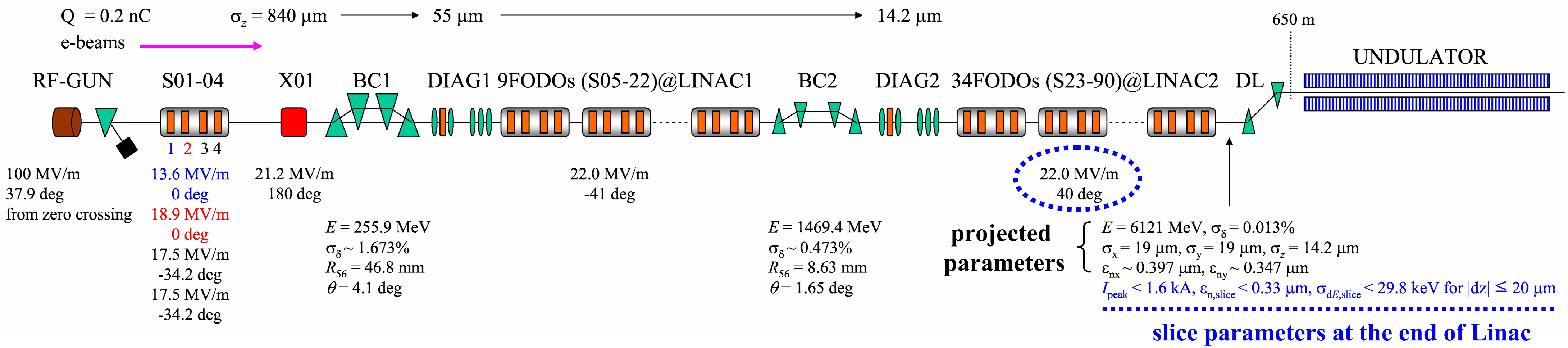
ε_{nx} ~ 0.397 μm, ε_{ny} ~ 0.347 μm

I_{peak} < 1.6 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 29.7 keV for |dz| ≤ 20 μm

Optimization-III of 6 GeV PSI-XFEL LINAC

PAUL SCHERRER INSTITUT

ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space chare, CSR, ISR, and wakefields !



Merits

- **lowest relative rms projected energy spread, $\sigma_\delta \sim 0.013\%$**
- **low projected emittance, $\varepsilon_{nx} \sim 0.40$ µm**
- **low slice emittance, $\varepsilon_{n,slice} \sim 0.33$ µm**
- **low rms slice energy spread, $\sigma_{dE,slice} \sim 148$ keV for whole bunch**
- **ideal energy chirpings for FEL1 & FEL2 (SASE) and FEL3 (Seeding) beamlines**

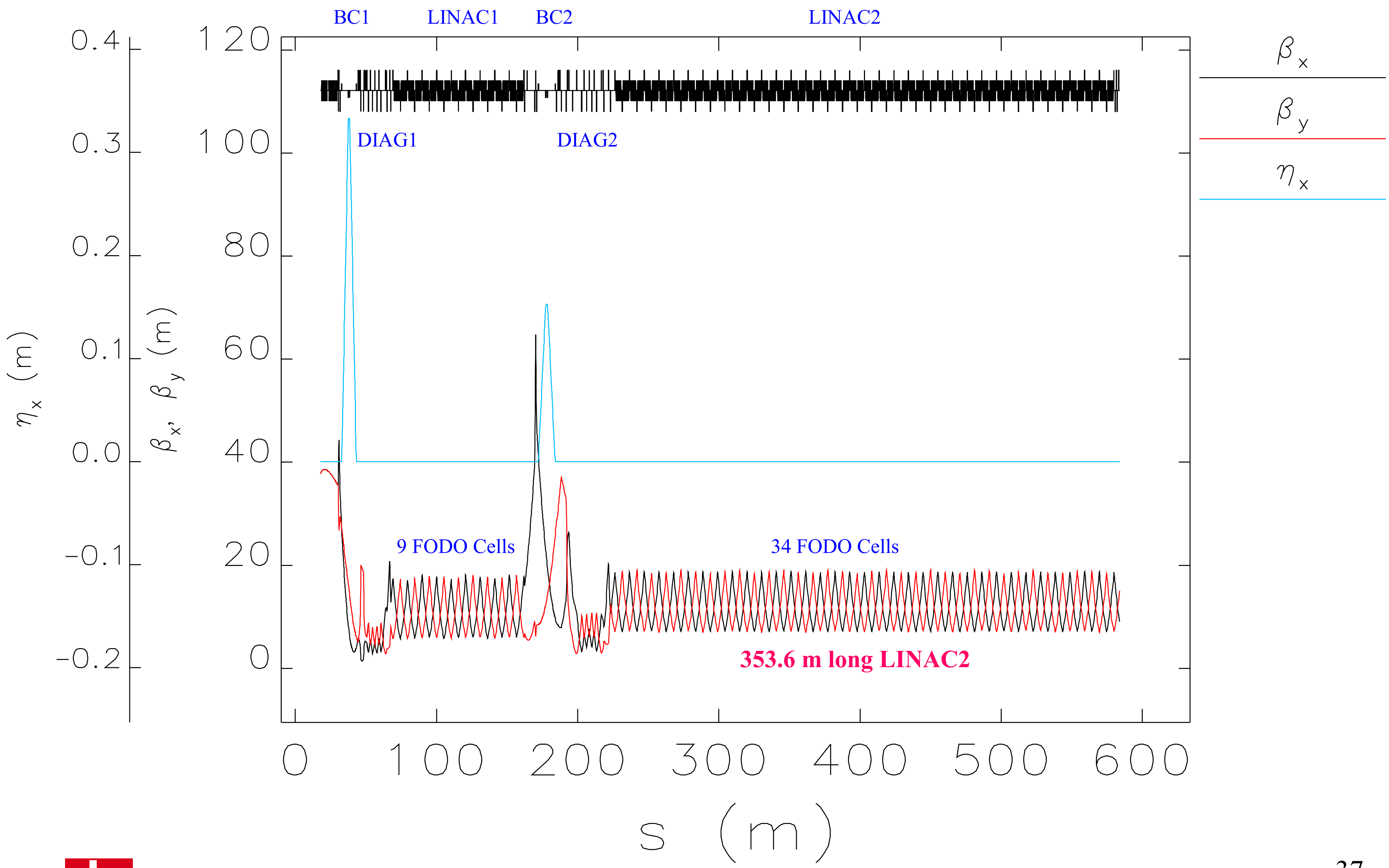
Demerits

- **somewhat long bunch length, $\sigma_z = 14.2$ µm and somewhat low peak current, $I_{peak} \sim 1.6$ kA**
- **longest machine length, z = 650 m† at the undulator entrance**

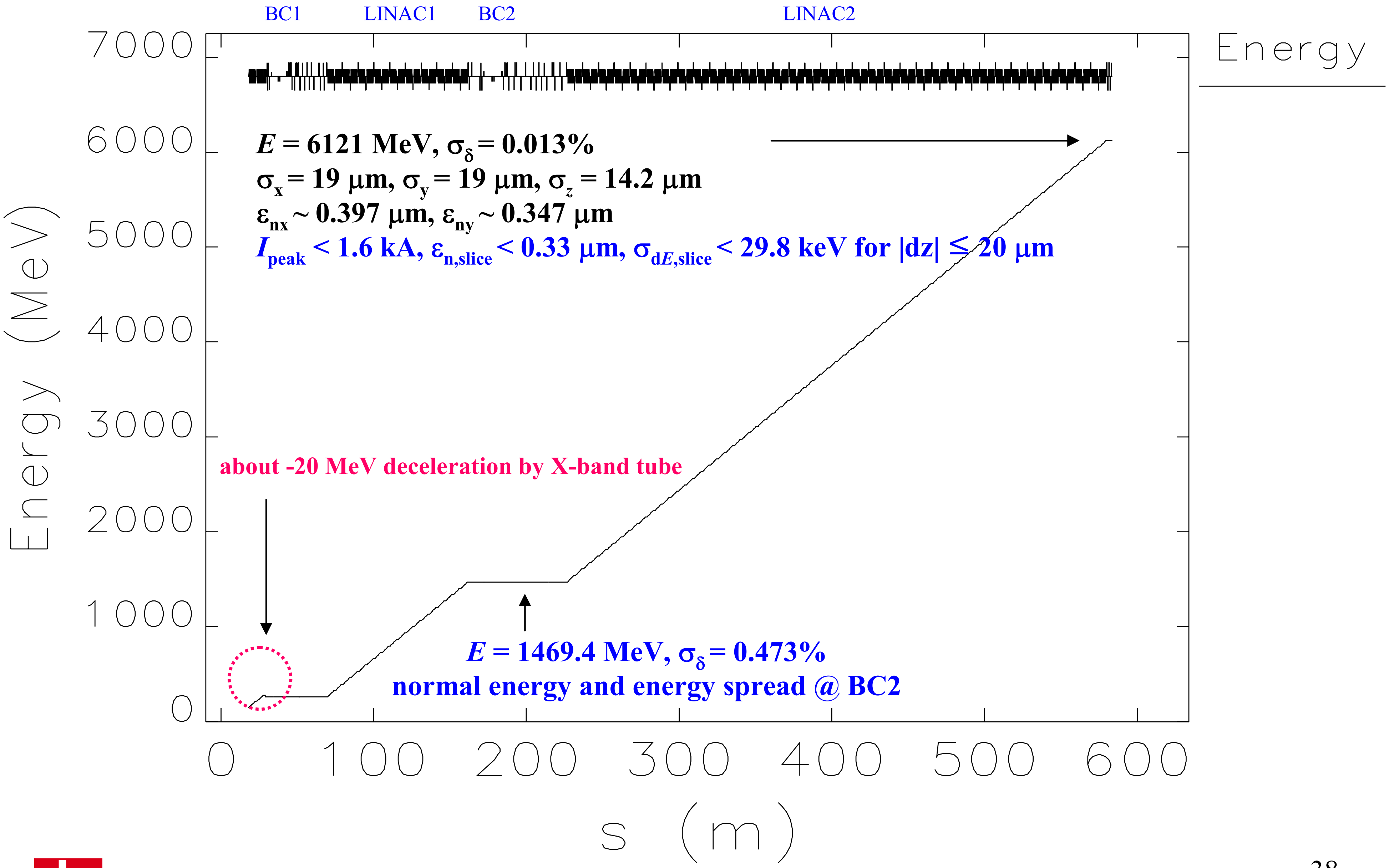
† : z = 650 m is the minimum length for 6 GeV Linac, Dog-Leg (DL), DIAG3 in DL, and Switch Yards in LINAC2

Optimization-III Optics of 6 GeV LINAC

PAUL SCHERRER INSTITUT

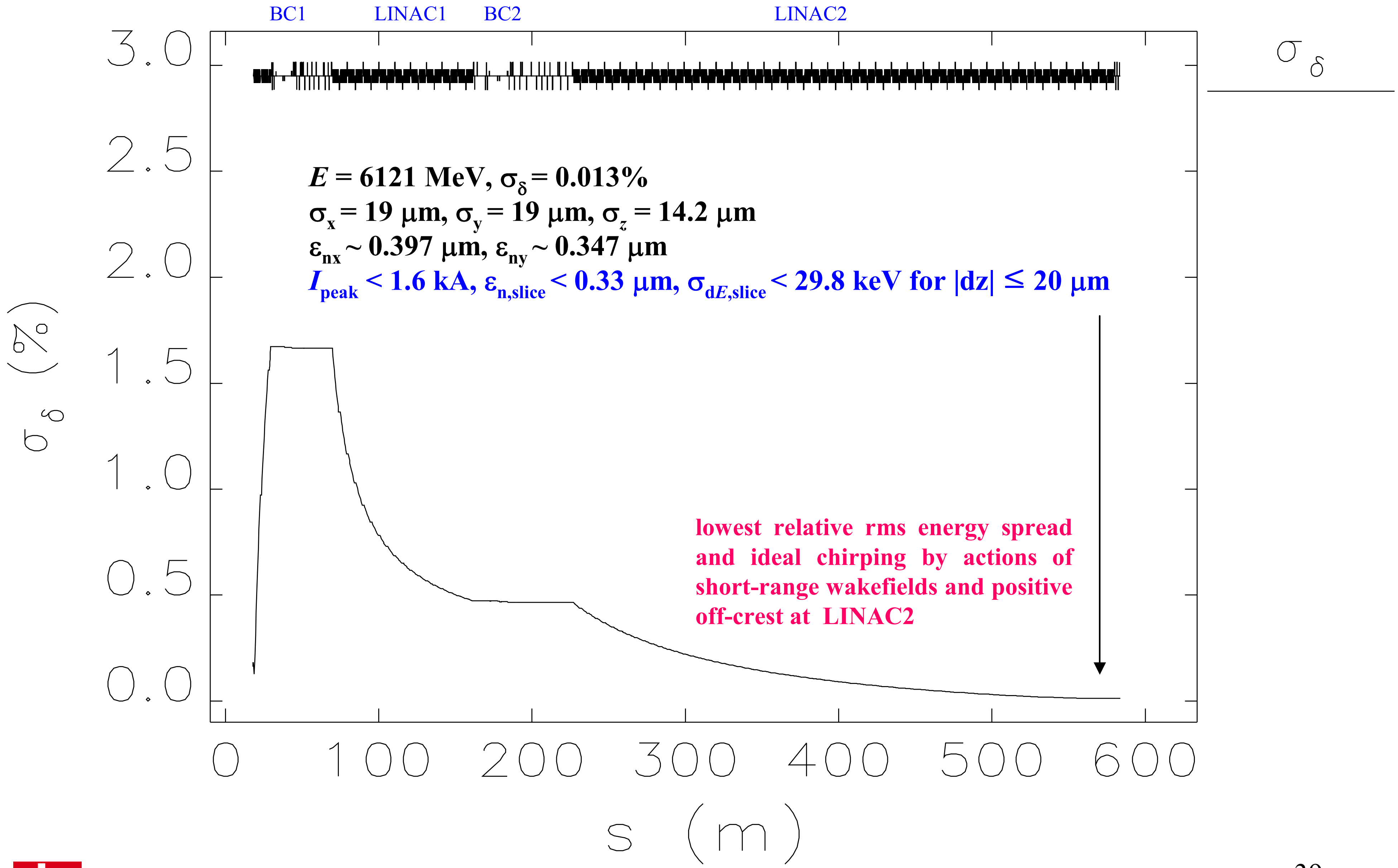


Optimization-III Beam Energy

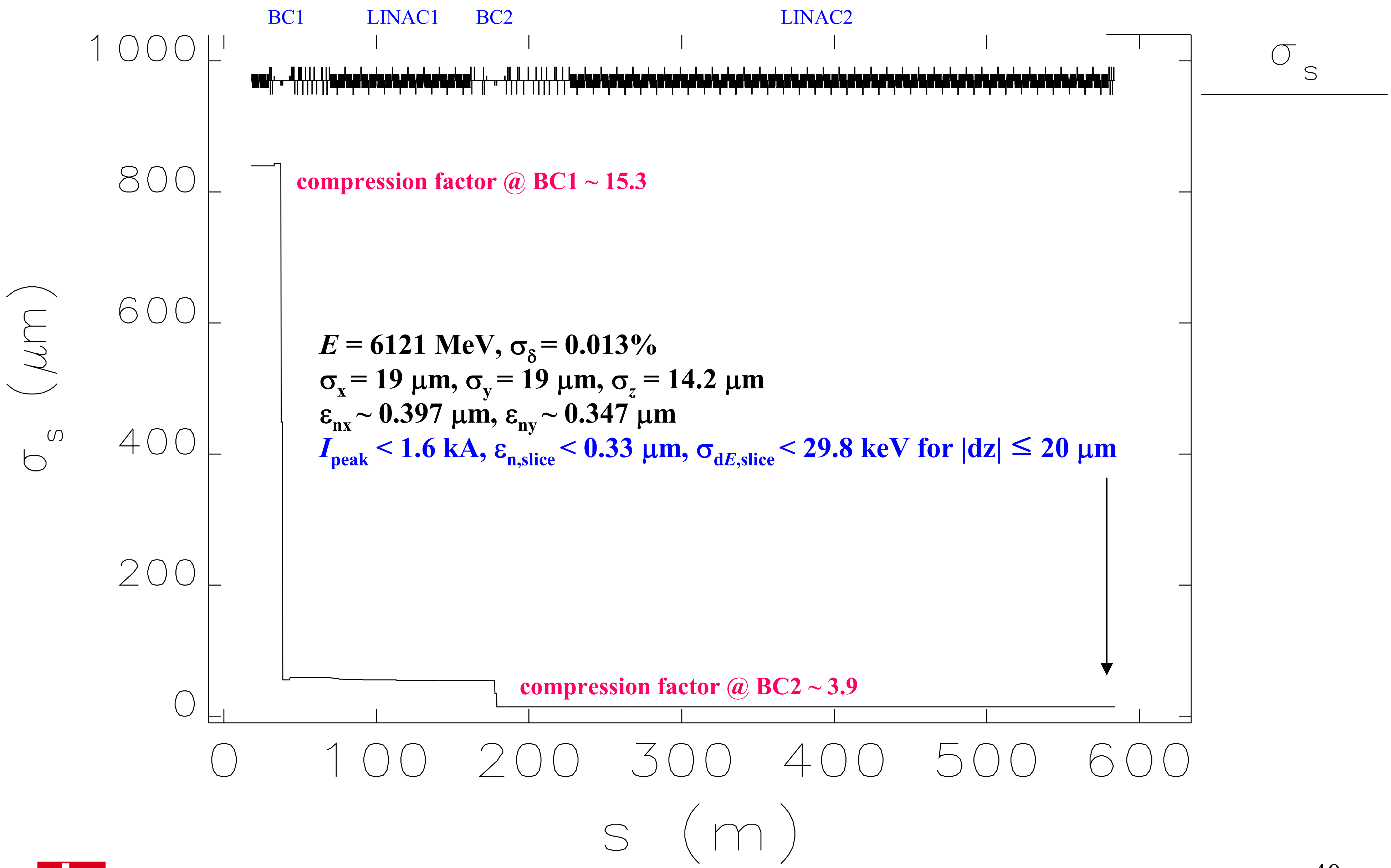


Optimization-III Projected Energy Spread

PAUL SCHERRER INSTITUT

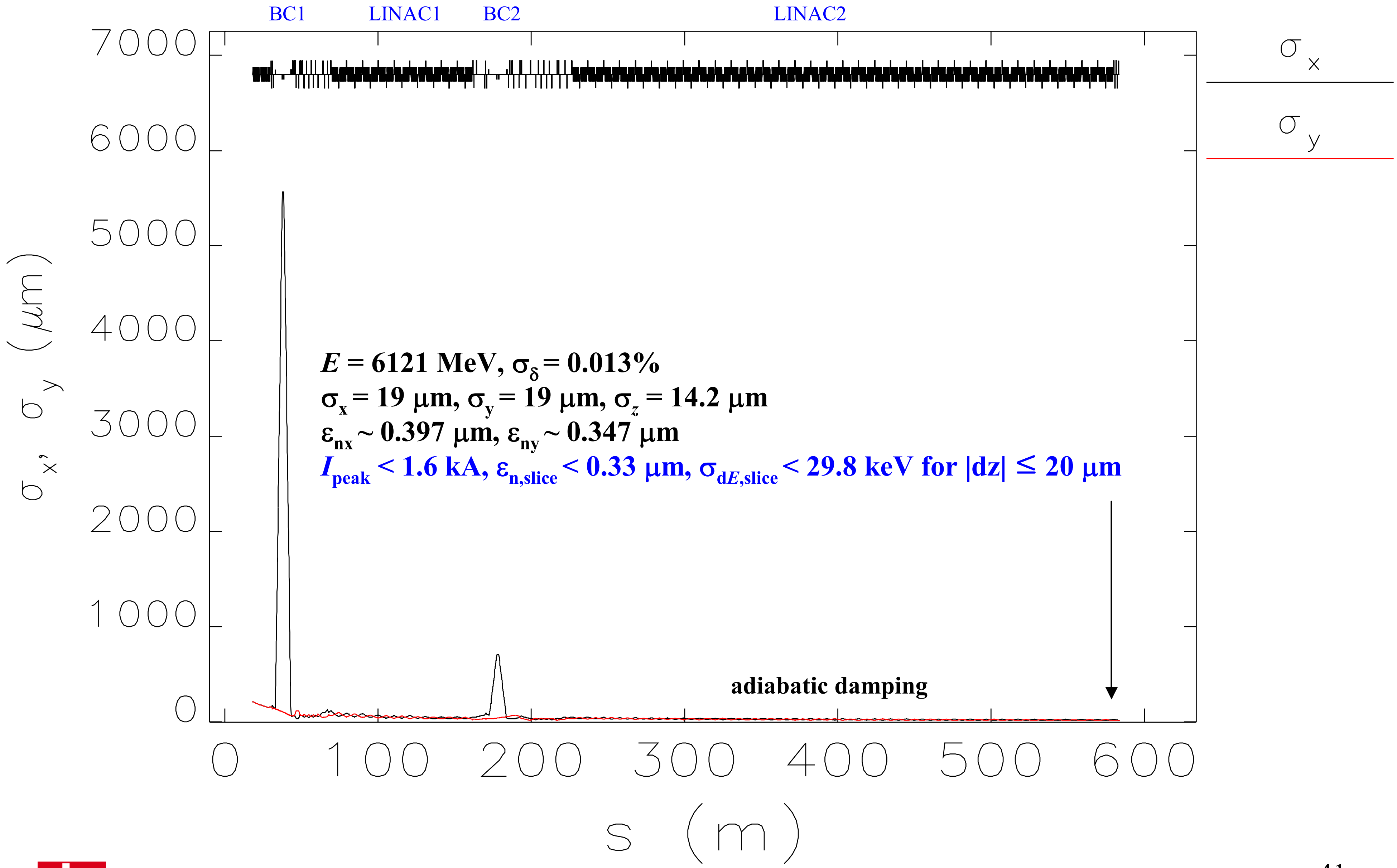


Optimization-III Bunch Length



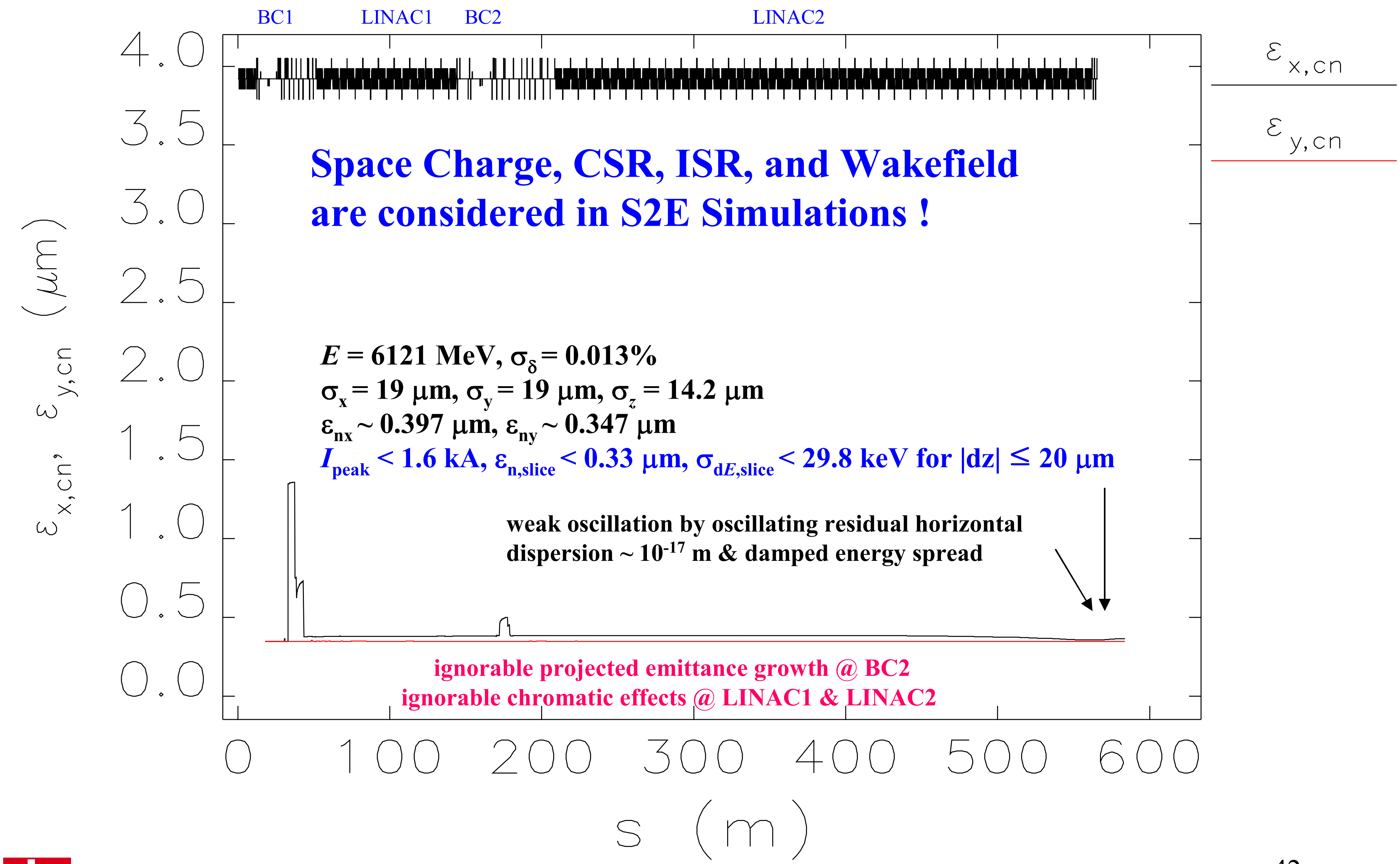
Optimization-III Transverse Beamsize

PAUL SCHERRER INSTITUT

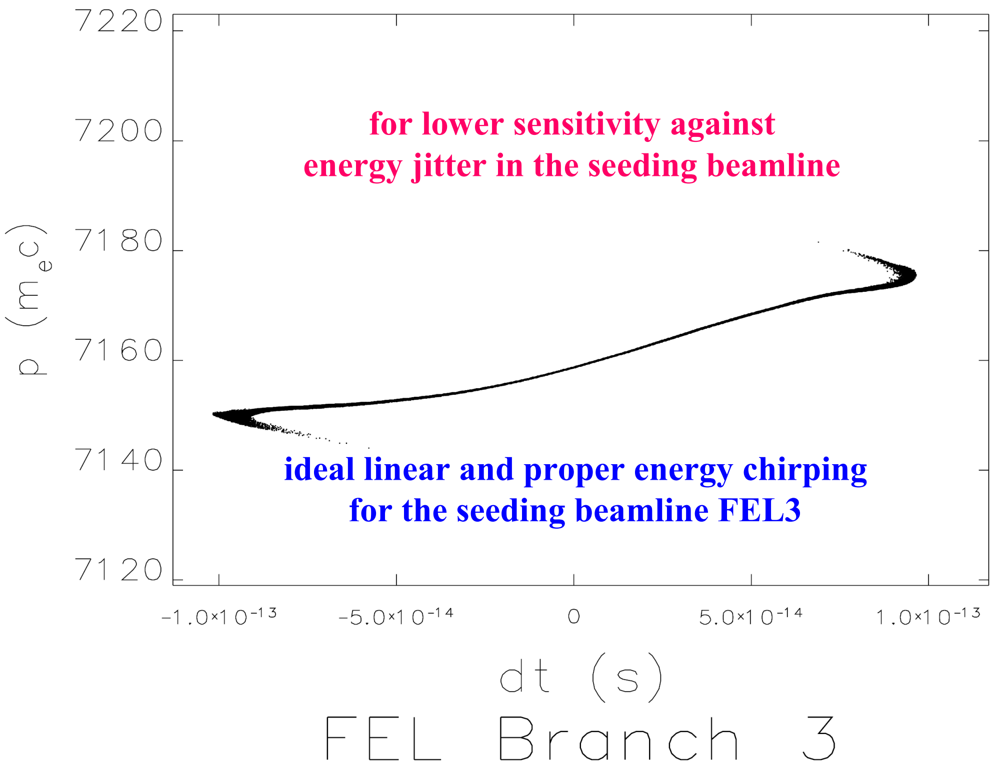


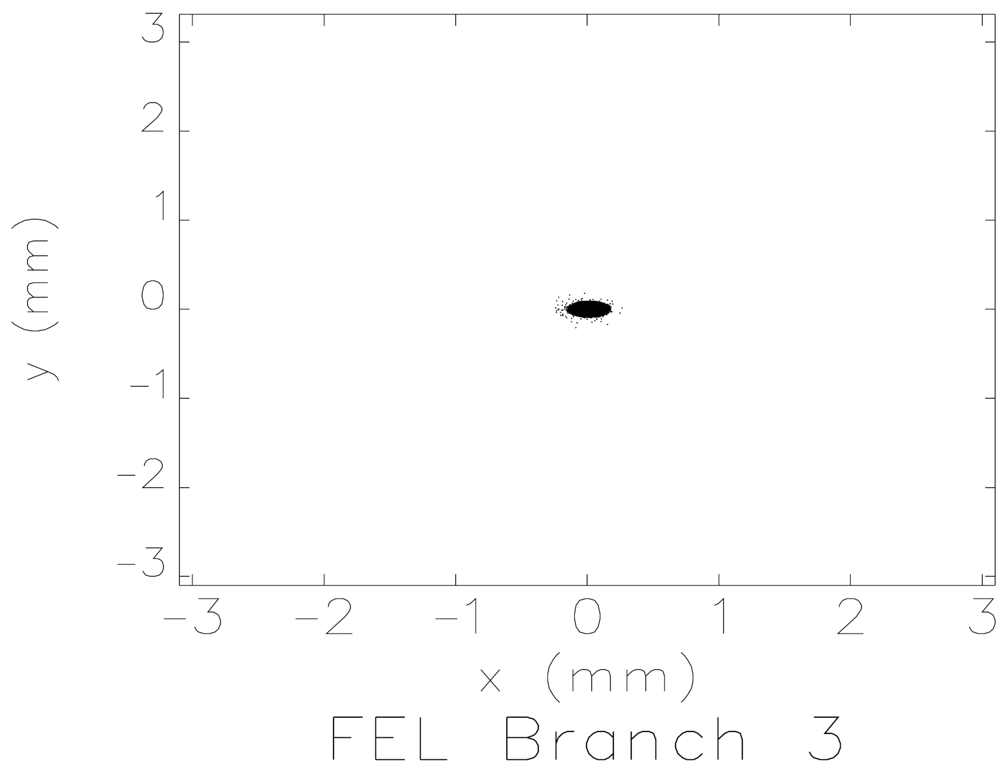
Optimization-III Projected Emittance

PAUL SCHERRER INSTITUT PSI



Optimization-III Phase Spaces at FEL3

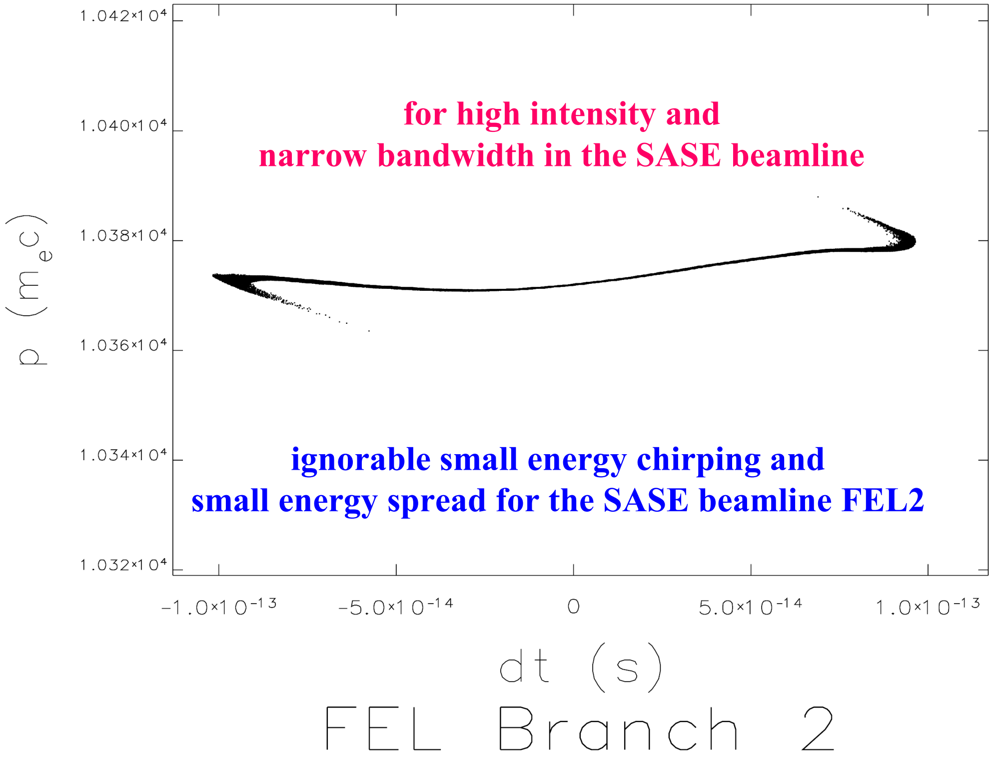


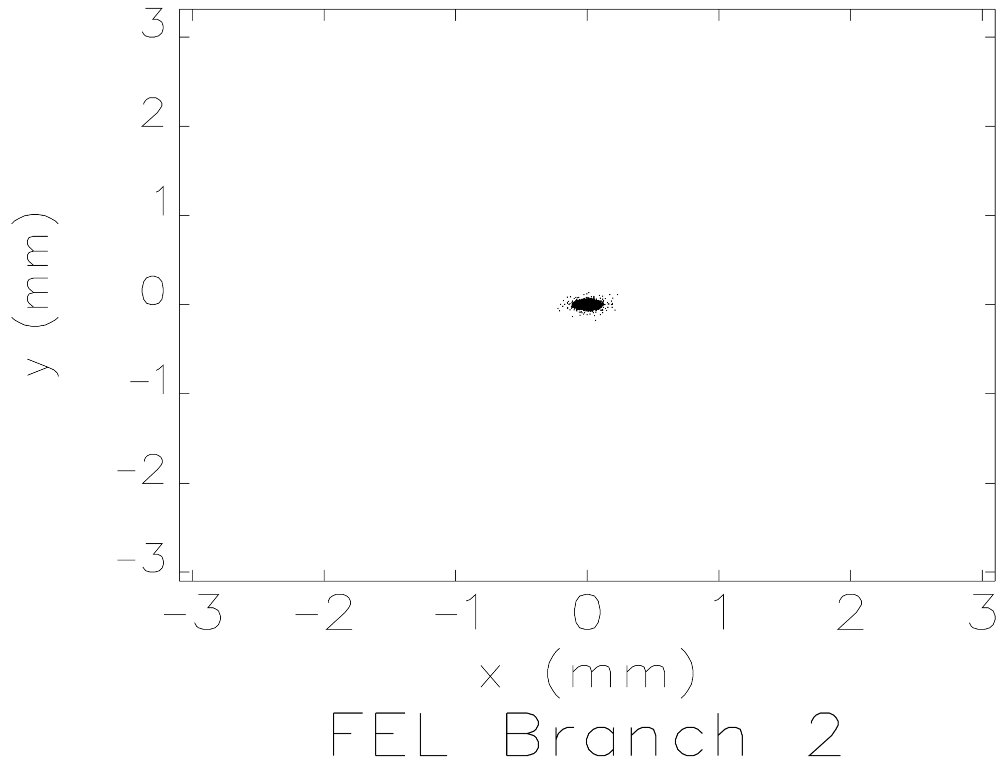


E = 3658 MeV, σ_δ = 0.098%
σ_x = 32 μm, σ_y = 19 μm, σ_z = 14.2 μm
$\varepsilon_{nx} \sim$ 0.397 μm, $\varepsilon_{ny} \sim$ 0.347 μm
I_{peak} < 1.6 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 29.8 keV for |dz| ≤ 20 μm

Sven Reiche finished GENESIS simulation to design FEL beamlines by using output of this optimization-III !

Optimization-III Phase Spaces at FEL2



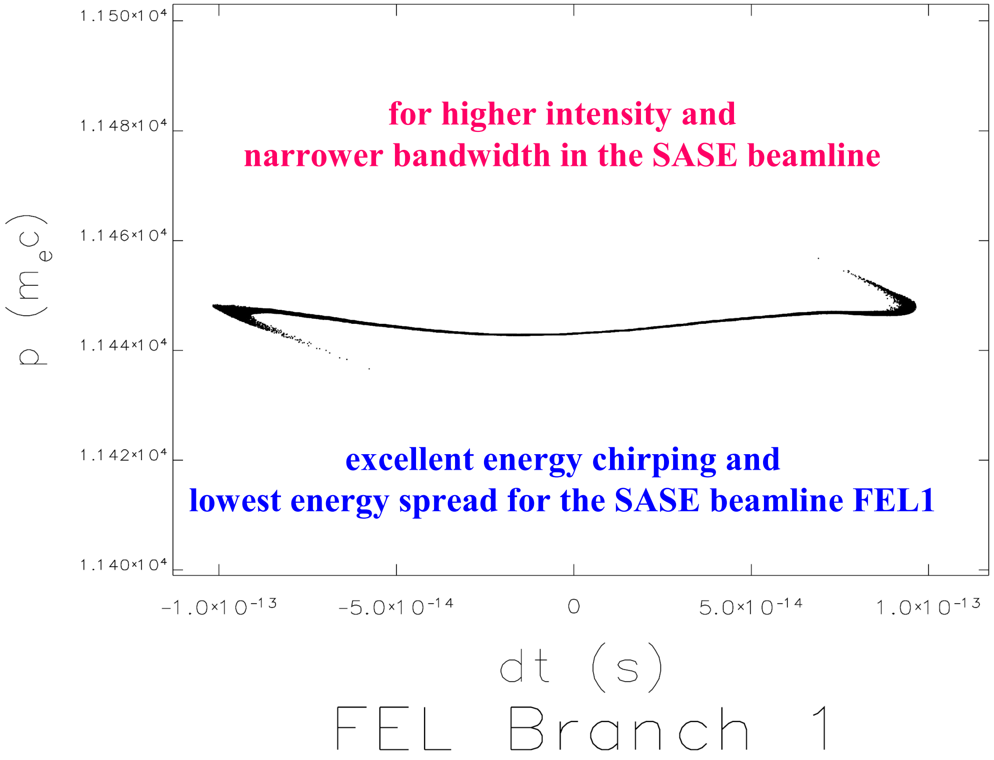


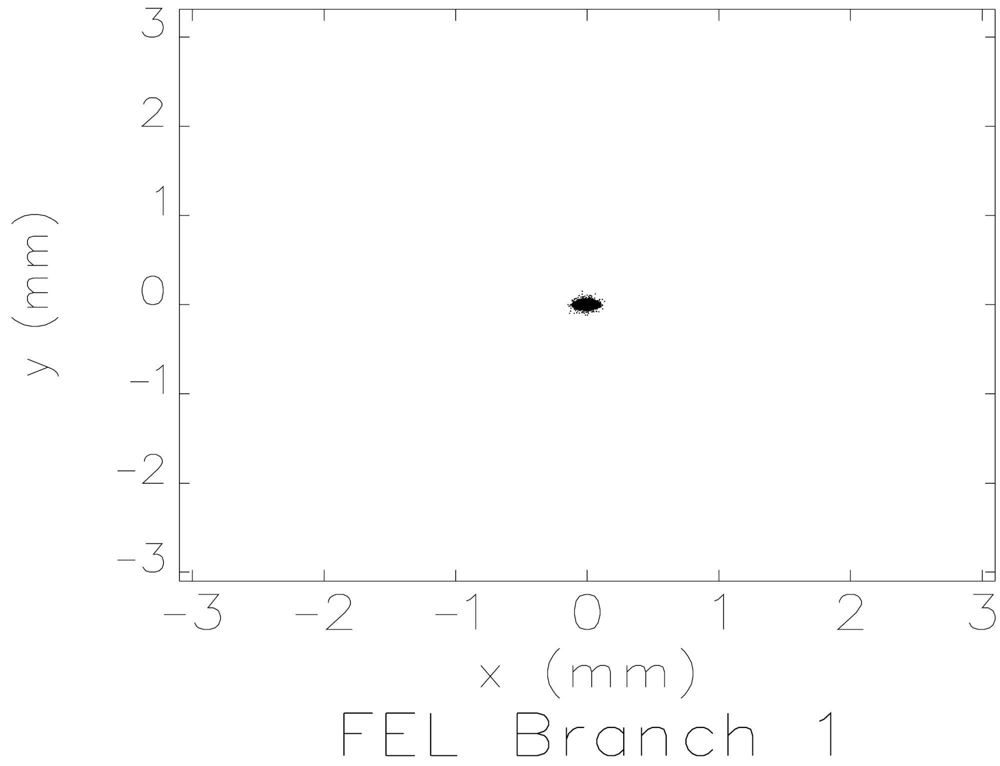
E = 5300 MeV, $\sigma_\delta = 0.024\%$
σ_x = 27 μm, σ_y = 15 μm, σ_z = 14.2 μm
$\varepsilon_{nx} \sim 0.397$ μm, $\varepsilon_{ny} \sim 0.347$ μm
$I_{peak} < 1.6$ kA, $\varepsilon_{n,slice} < 0.33$ μm, $\sigma_{dE,slice} < 29.8$ keV for $|dz| \leq 20$ μm

Sven Reiche finished GENESIS simulation to design FEL beamlines by using output of this optimization-III !

Optimization-III Phase Spaces at FEL1

PAUL SCHERRER INSTITUT

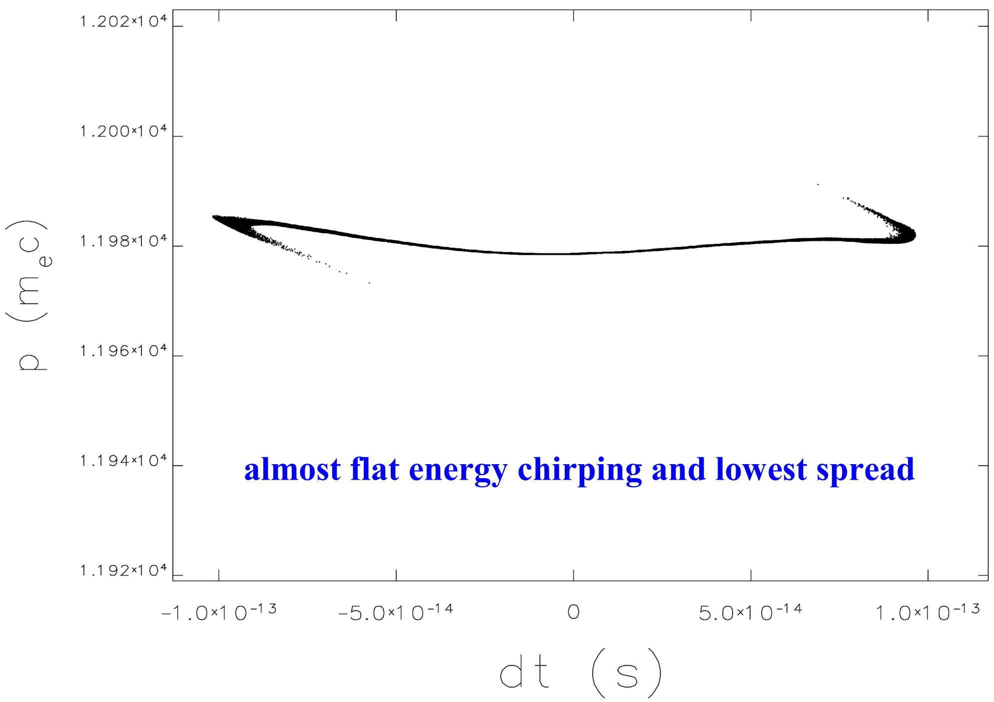




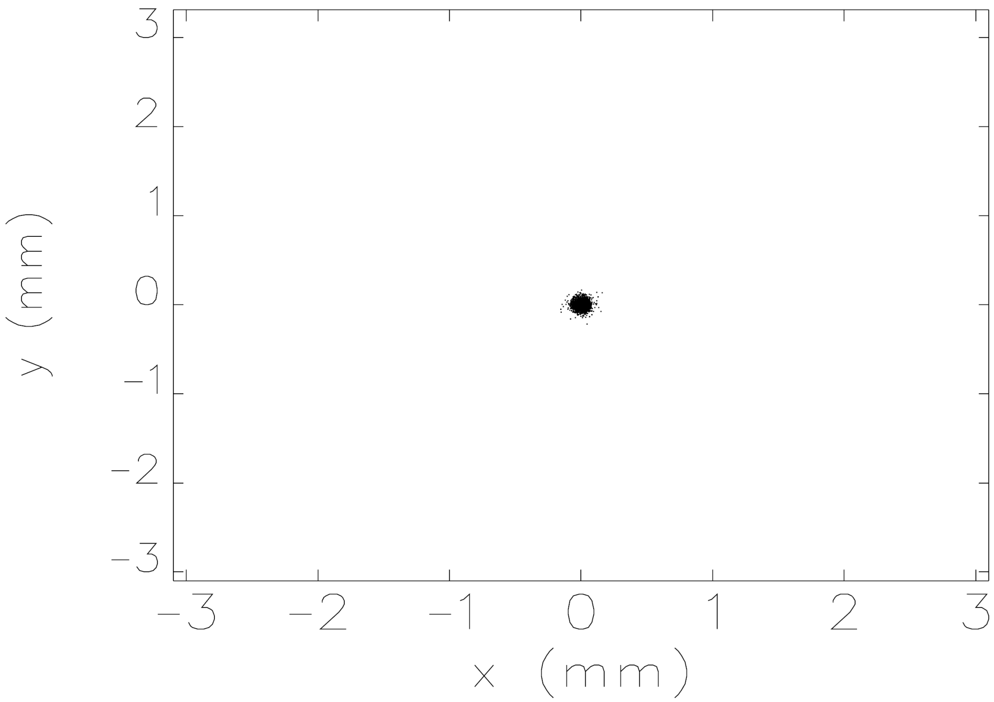
E = 5848 MeV, σ_δ = 0.013%
σ_x = 26 μm, σ_y = 15 μm, σ_z = 14.2 μm
ε_{nx} ~ 0.397 μm, ε_{ny} ~ 0.347 μm
I_{peak} < 1.6 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 29.8 keV for |dz| ≤ 20 μm

Sven Reiche started GENESIS simulation to design FEL beamlines by using output of this optimization-III !

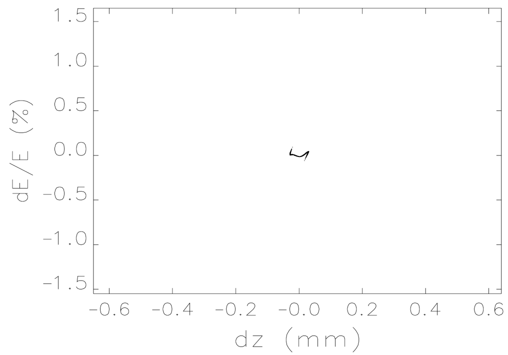
Optimization-III Phase Spaces at 6 GeV



End of LINAC



End of LINAC



End of LINAC

E = 6121 MeV, σ_δ = 0.013%
σ_x = 19 μm, σ_y = 19 μm, σ_z = 14.2 μm
ε_{nx} ~ 0.397 μm, ε_{ny} ~ 0.347 μm
I_{peak} < 1.6 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 29.8 keV for |dz| ≤ 20 μm

Optimization-III Slice Parameters at 6 GeV

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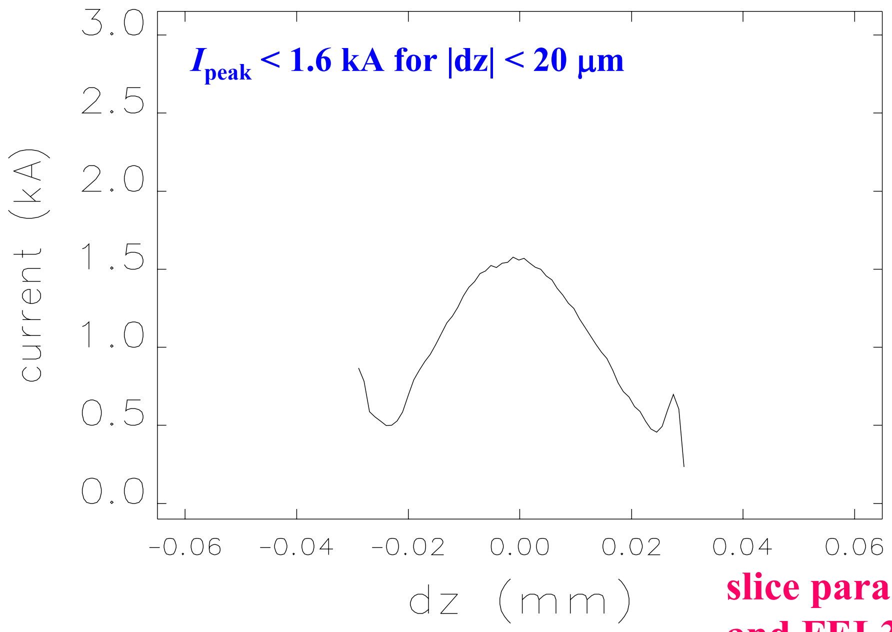
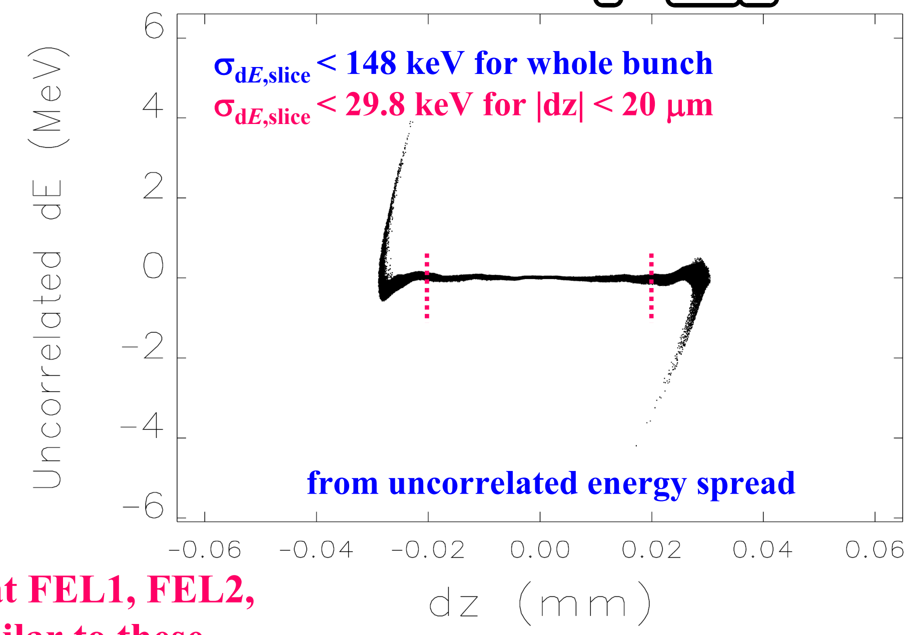
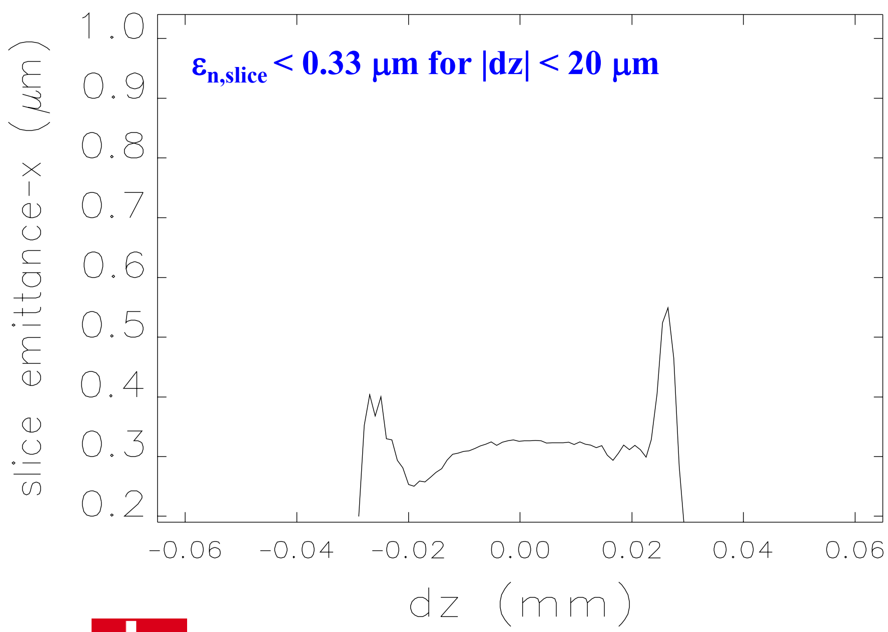
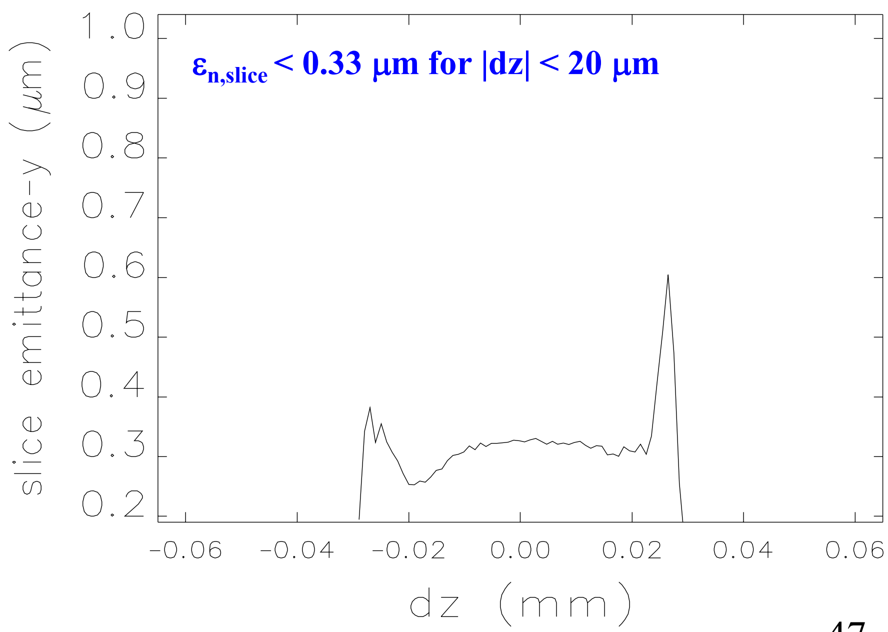




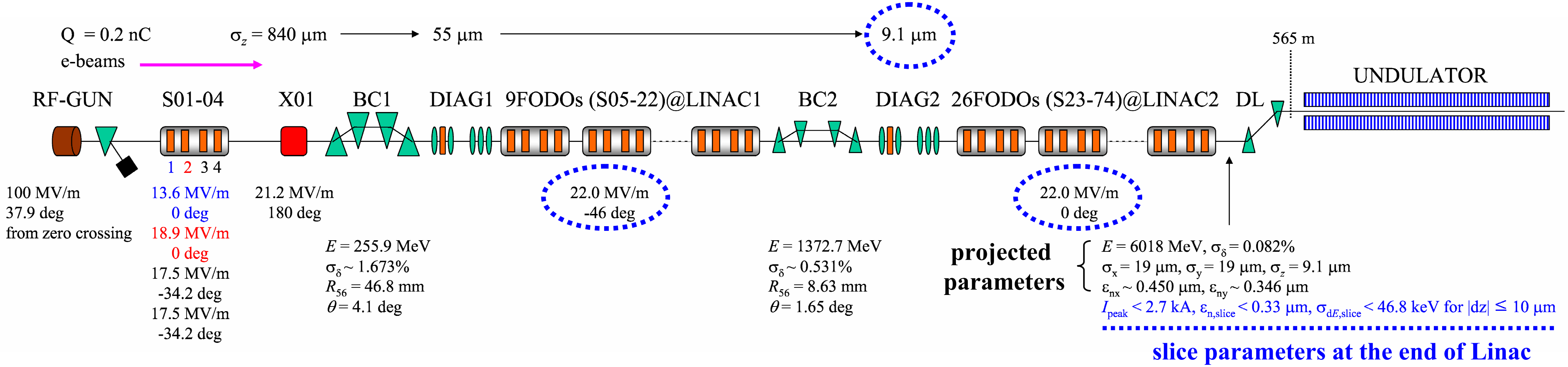
slice parameters at FEL1, FEL2, and FEL3 are similar to these.





Optimization-IV of 6 GeV PSI-XFEL LINAC

ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space chare, CSR, ISR, and wakefields !



Merits

- short bunch length, σ_z = 9.1 μm and high peak current, I_{peak} ~ 2.7 kA
- low slice emittance, $\varepsilon_{n,slice}$ ~ 0.33 μm
- shortest machine length, z = 565 m† at the undulator entrance

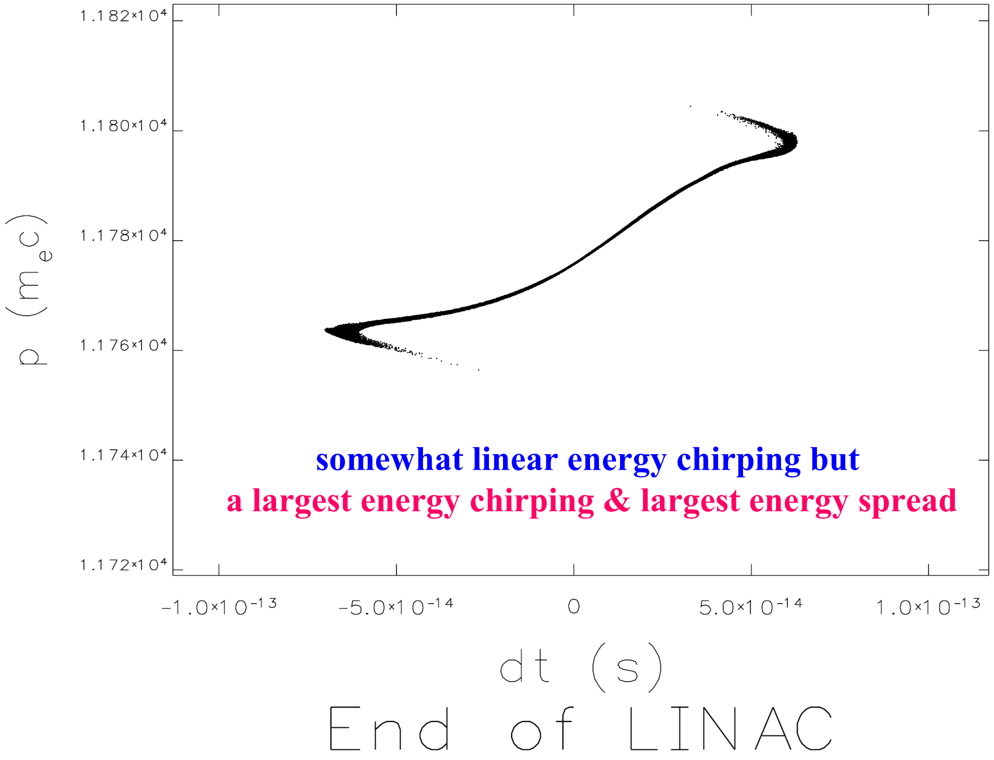
Demerits

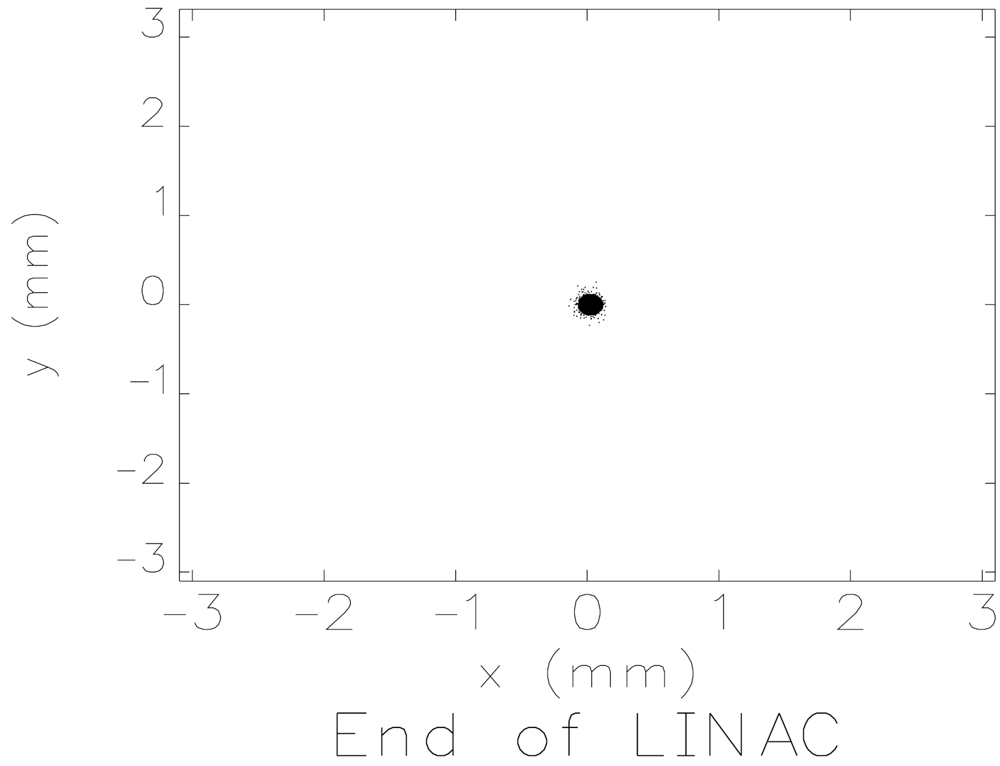
- somewhat higher projected emittance, ε_{nx} ~ 0.45 μm
- highest relative rms projected energy spread at BC2 and at the end of linac, σ_δ ~ 0.082%
- higher rms slice energy spread, $\sigma_{dE,slice}$ ~ 211 keV for whole bunch
- somewhat nonlinear and large energy chirping

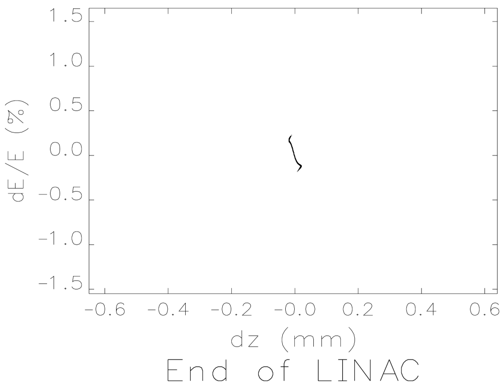
† : z = 565 m is the minimum length for 6 GeV Linac, Dog-Leg (DL), DIAG3 in DL, and Switch Yards in LINAC2

Optimization-IV Phase Spaces at 6 GeV

PAUL SCHERRER INSTITUT







E = 6018 MeV, σ_δ = 0.082%

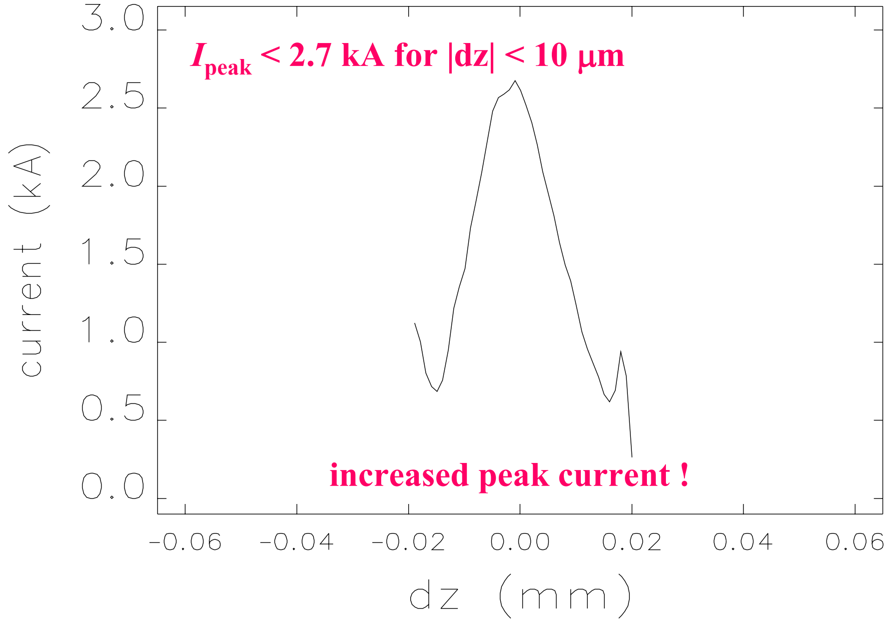
σ_x = 19 µm, σ_y = 19 µm, σ_z = 9.1 µm

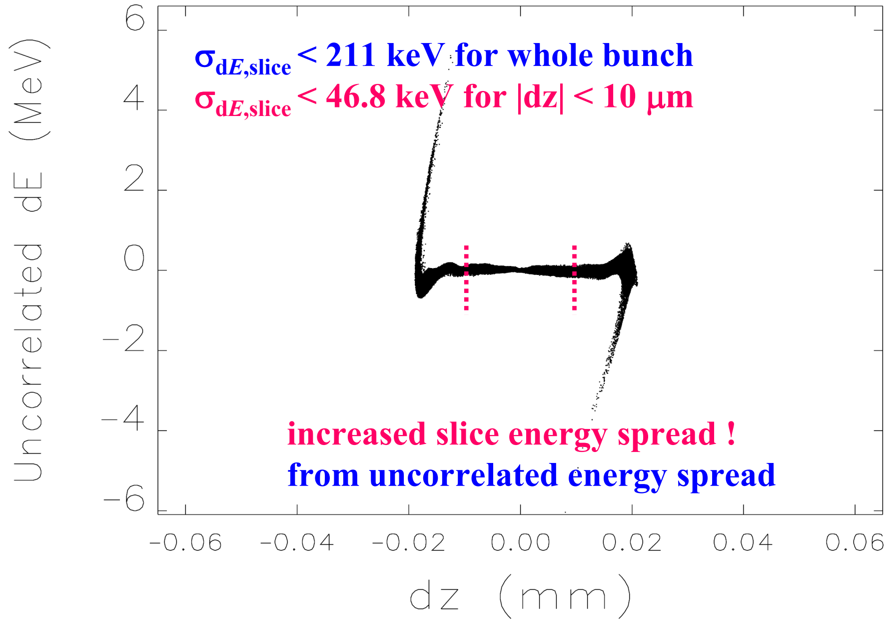
ε_{nx} ~ 0.450 µm, ε_{ny} ~ 0.346 µm

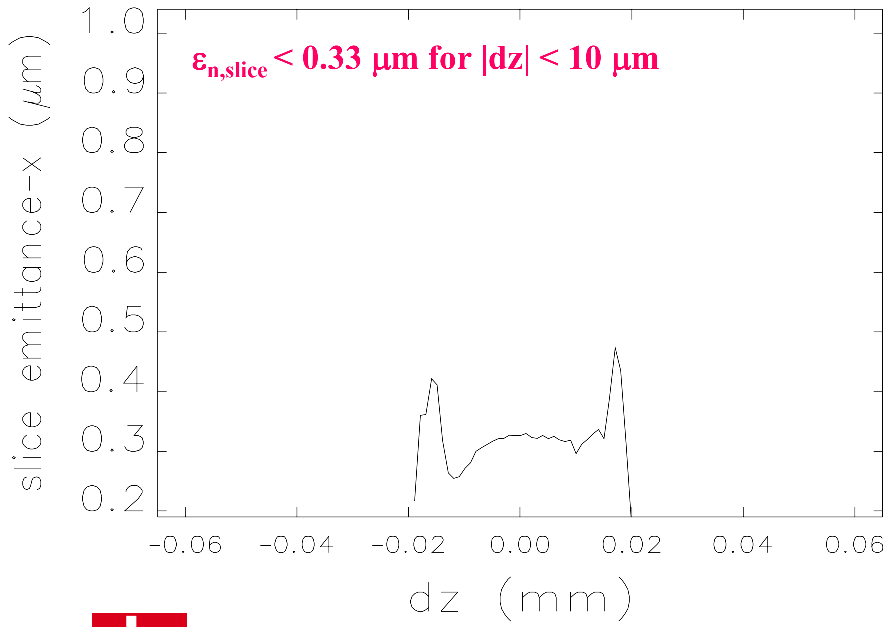
I_{peak} < 2.7 kA, $\varepsilon_{n,slice}$ < 0.33 µm, $\sigma_{dE,slice}$ < 46.8 keV for |dz| ≤ 10 µm

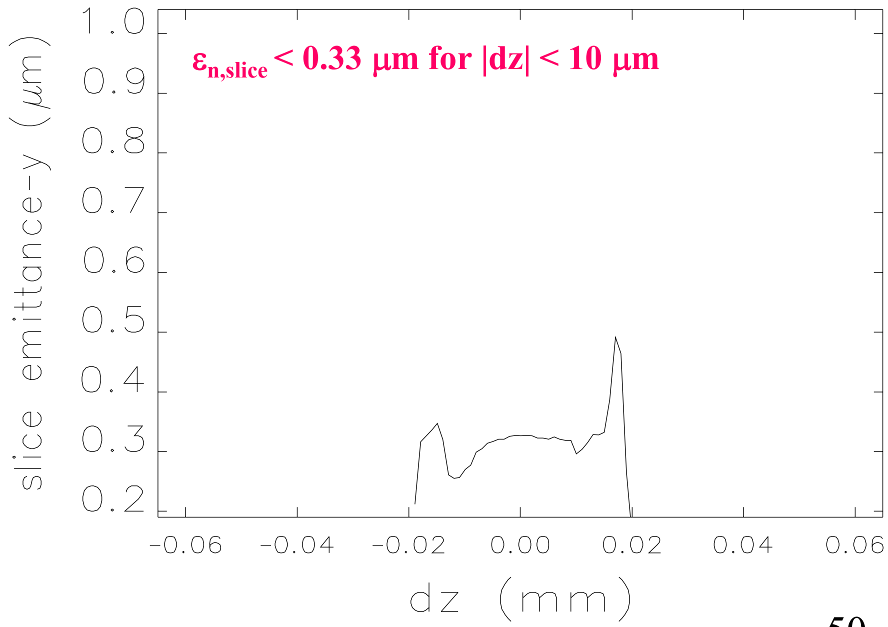
Optimization-IV Slice Parameters at 6 GeV

PAUL SCHERRER INSTITUT PSI





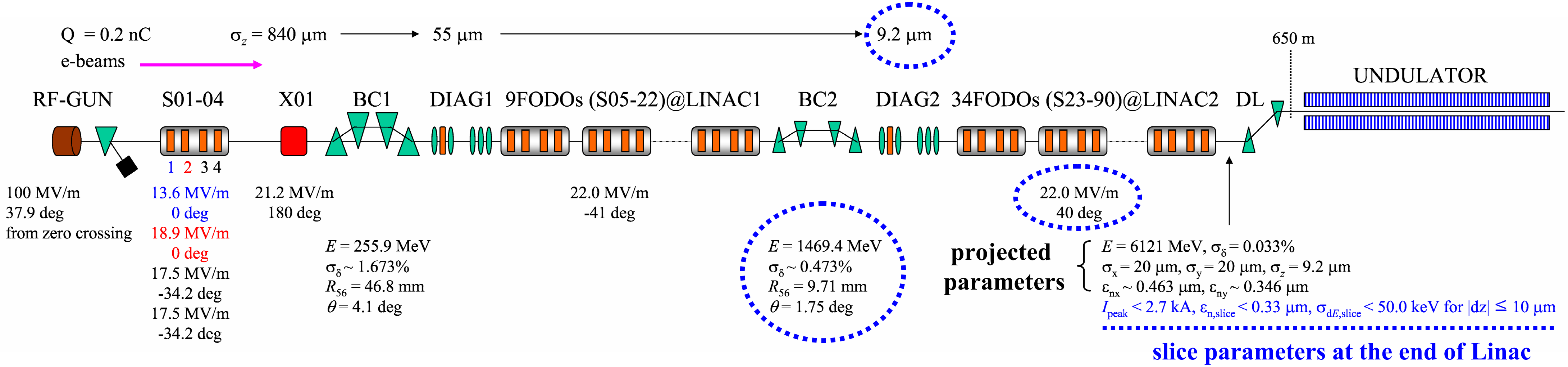




Optimization-V of 6 GeV PSI-XFEL LINAC

PAUL SCHERRER INSTITUT

ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space chare, CSR, ISR, and wakefields !



Merits

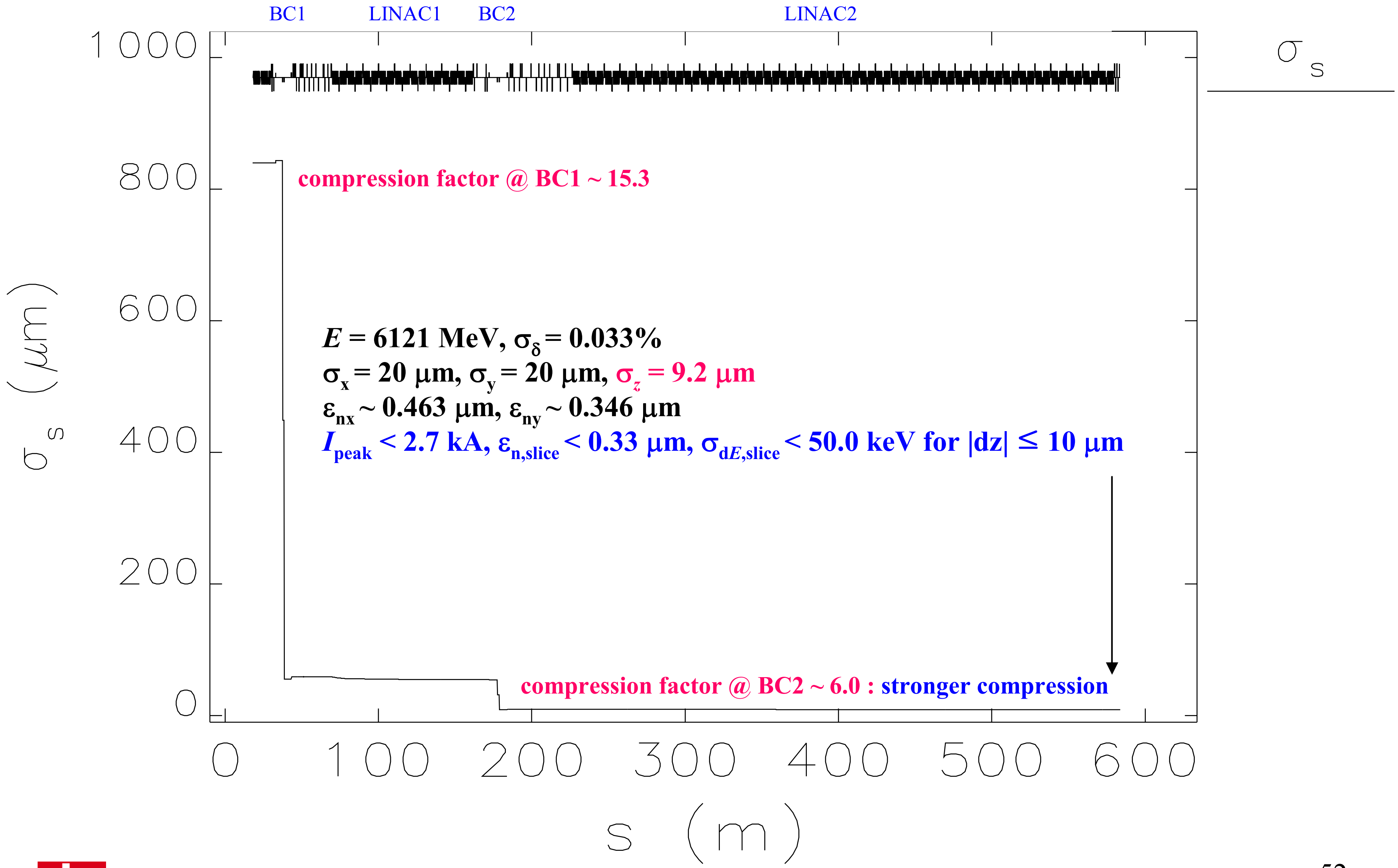
- **short bunch length, σ_z = 9.2 μm and high peak current, I_{peak} ~ 2.7 kA**
- **low relative rms projected energy spread at BC2 and at the end of linac, σ_δ ~ 0.033%**
- **improved energy chirping for FEL1 & FEL2 (SASE) and FEL3 (Seeding) beamlines**
- **low slice emittance, $\varepsilon_{n,slice}$ ~ 0.33 μm**

Demerits

- **longest machine length, z = 650 m† at the undulator entrance**
- **somewhat higher projected emittance, ε_{nx} ~ 0.46 μm**
- **higher rms slice energy spread, $\sigma_{dE,slice}$ ~ 210.4 keV for whole bunch**

† : z = 650 m is the minimum length for 6 GeV Linac, Dog-Leg (DL), DIAG3 in DL, and Switch Yards in LINAC2

Optimization-V Bunch Length



Optimization-V Projected Emittance

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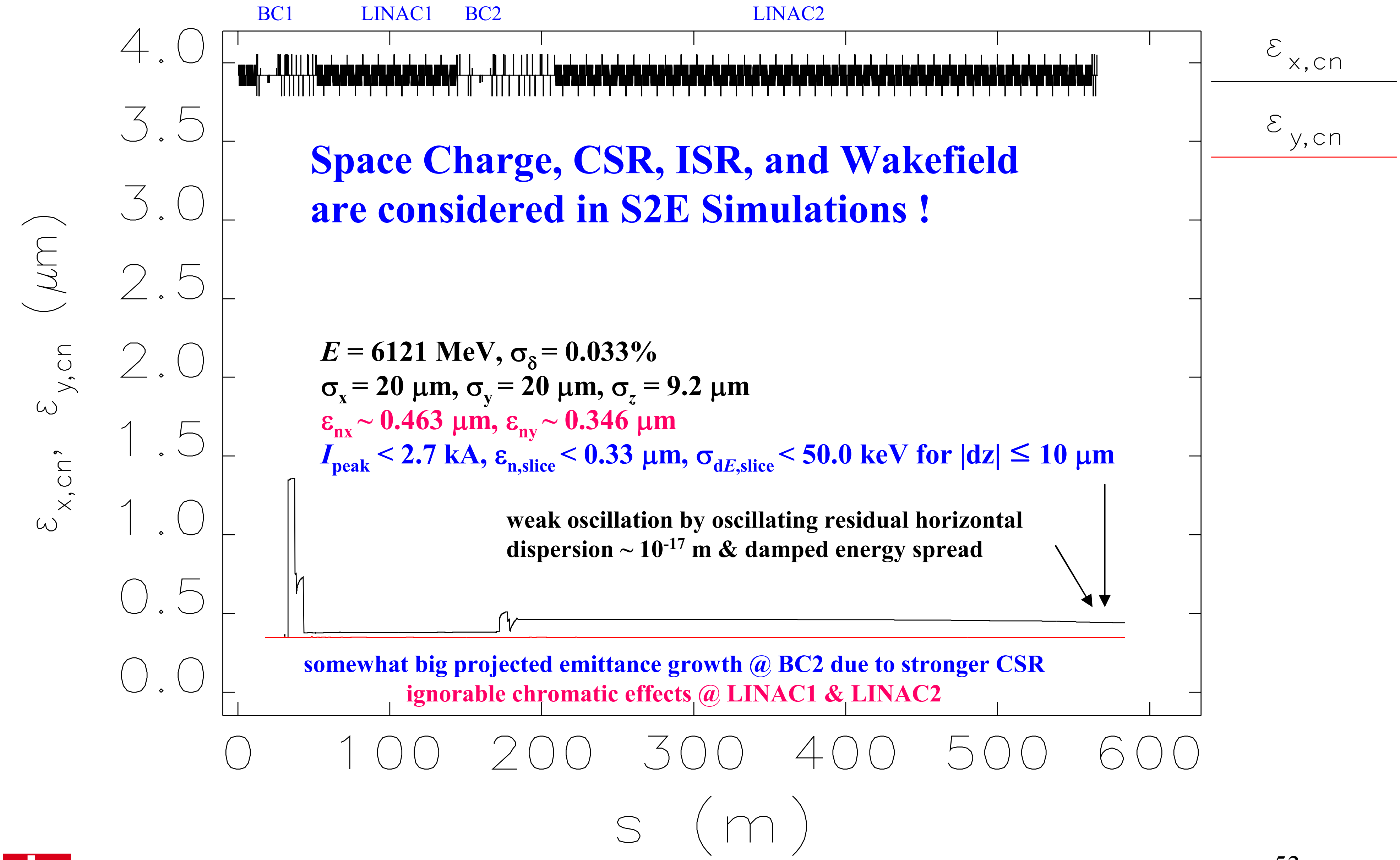

Optimization-V Phase Spaces at FEL3

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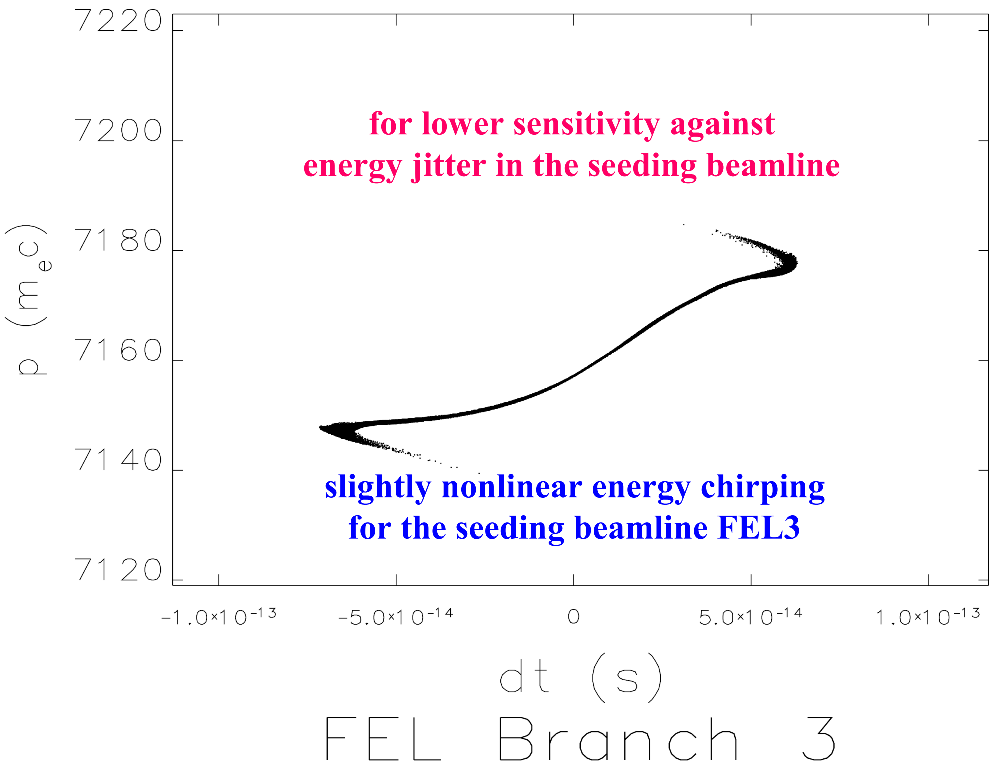
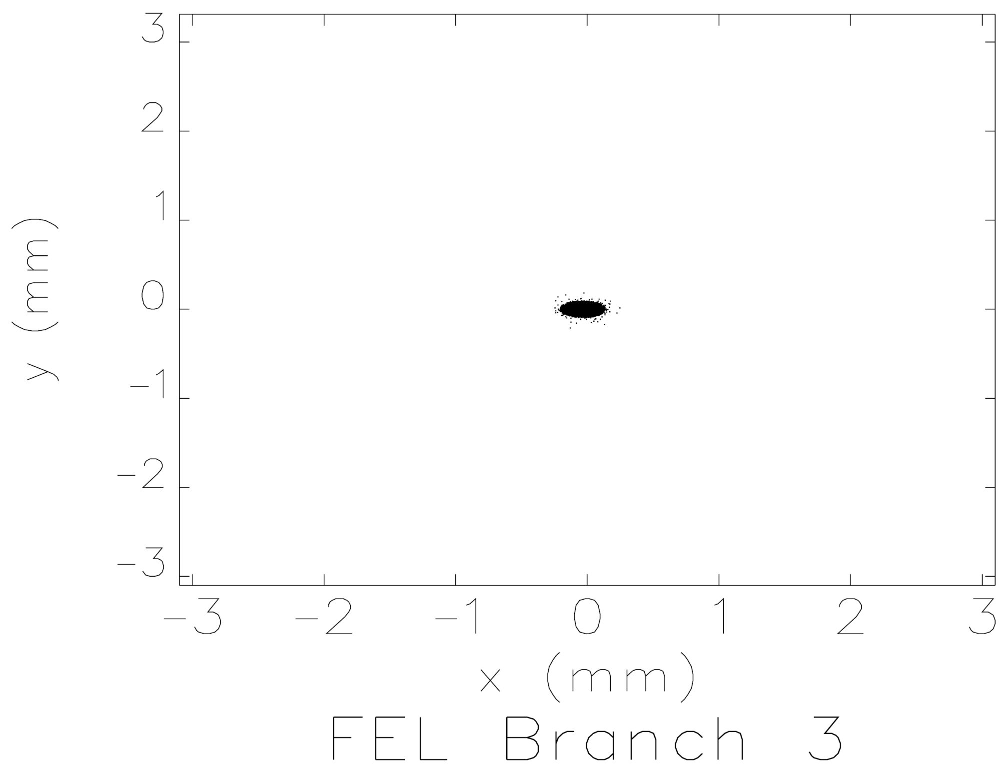




E = 3658 MeV, σ_δ = 0.127%

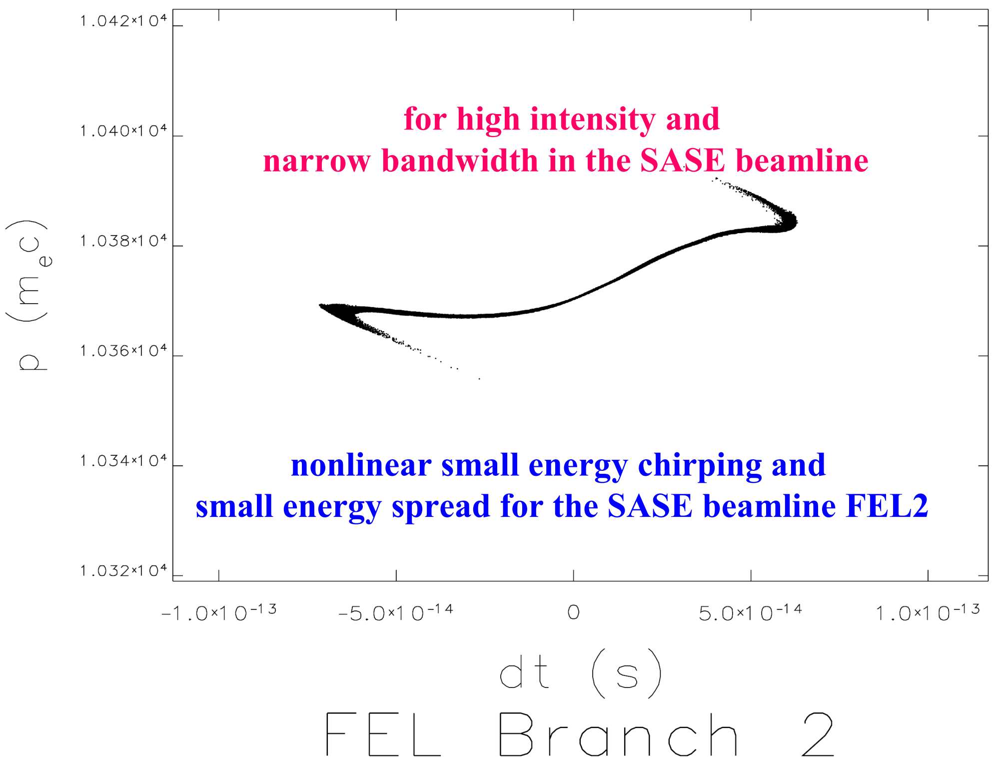
σ_x = 36 μm, σ_y = 20 μm, σ_z = 9.2 μm

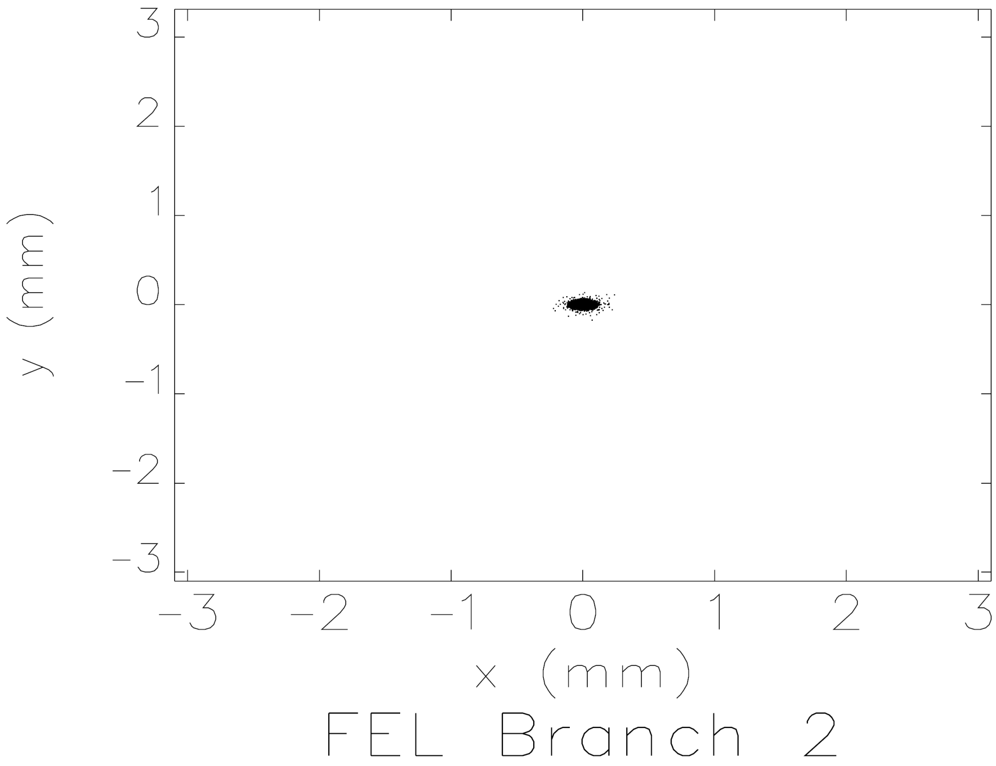
ε_{nx} ~ 0.463 μm, ε_{ny} ~ 0.346 μm

I_{peak} < 2.7 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 50.0 keV for |dz| ≤ 10 μm

Sven Reiche finished GENESIS simulation to design FEL beamlines by using output of this optimization-V !

Optimization-V Phase Spaces at FEL2





E = 5300 MeV, σ_δ = 0.052%
σ_x = 27 μm, σ_y = 15 μm, σ_z = 9.2 μm
$\varepsilon_{nx} \sim$ 0.463 μm, $\varepsilon_{ny} \sim$ 0.346 μm
I_{peak} < 2.7 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 50.0 keV for |dz| ≤ 10 μm

Sven Reiche finished GENESIS simulation to design FEL beamlines by using output of this optimization-V !

Optimization-V Phase Spaces at FEL1

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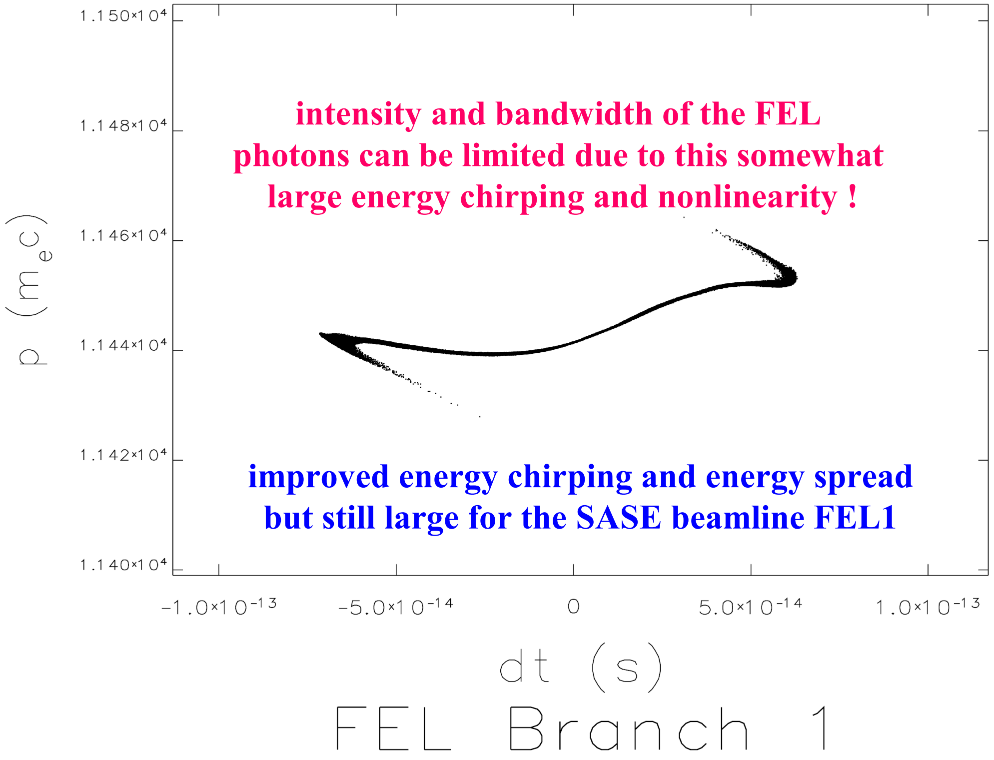
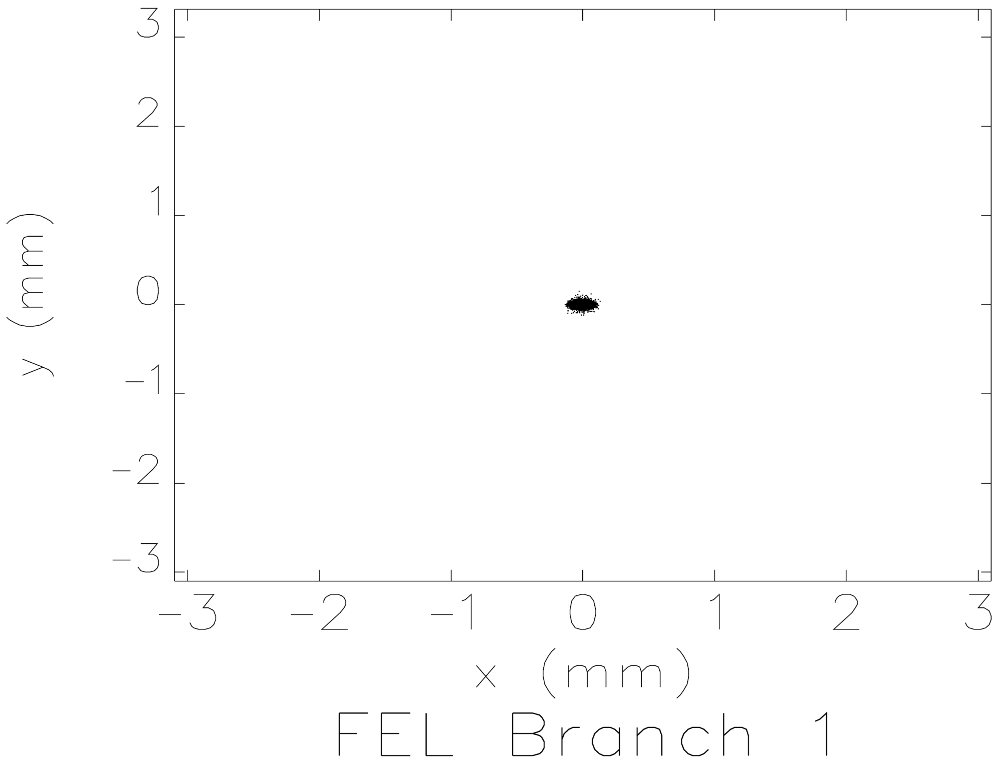
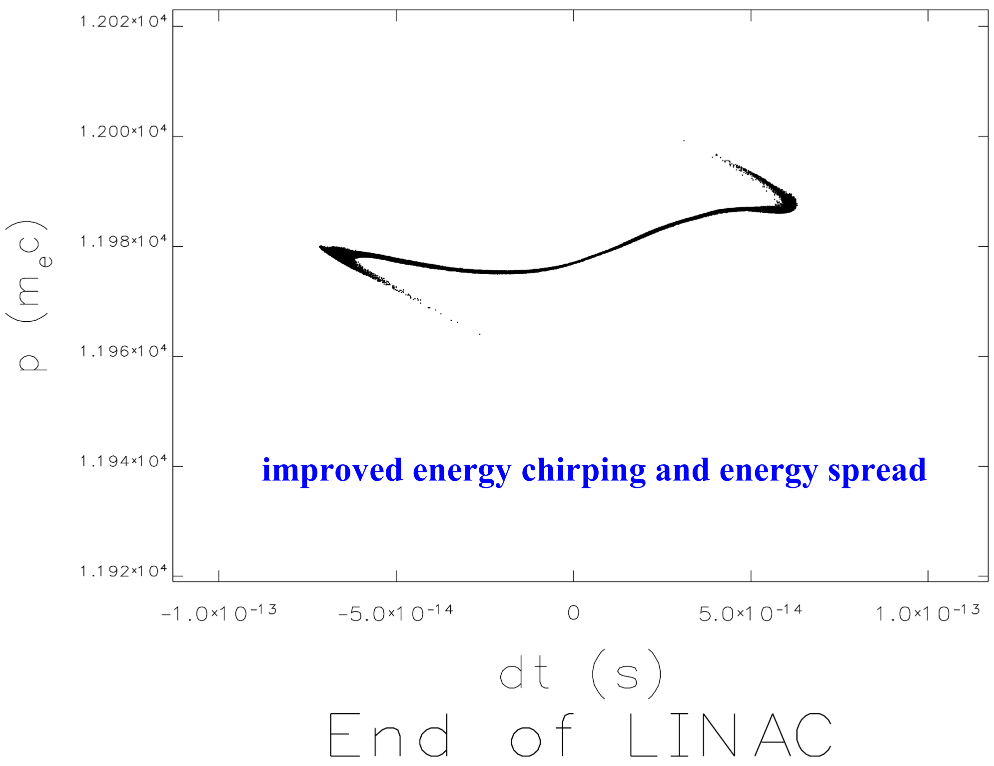


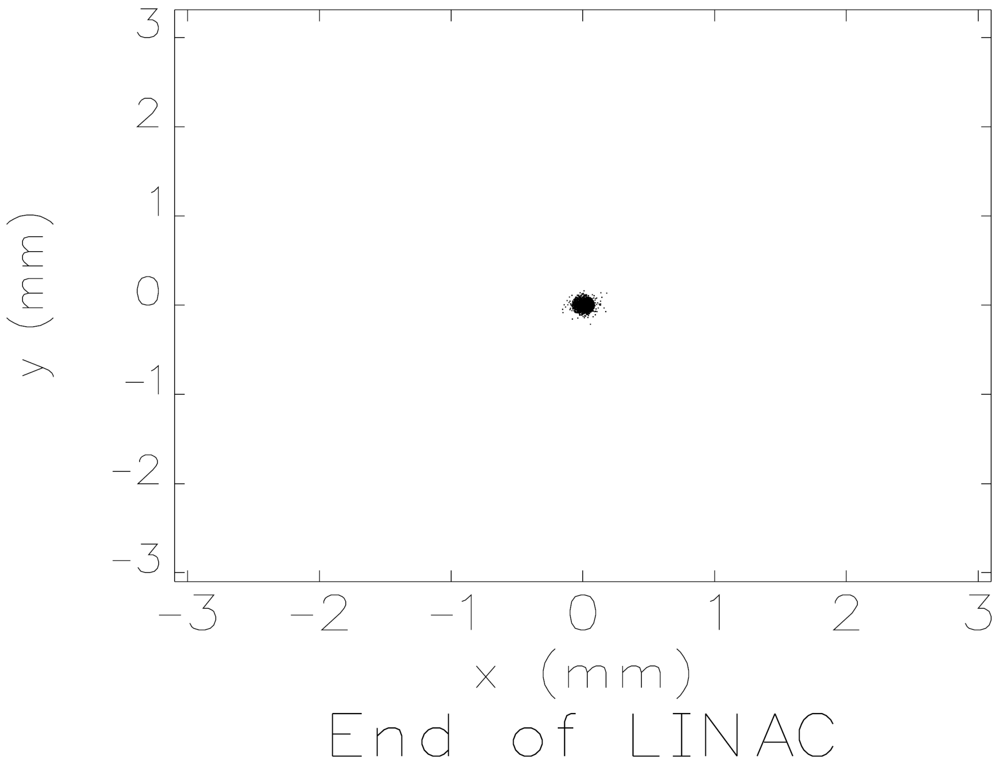


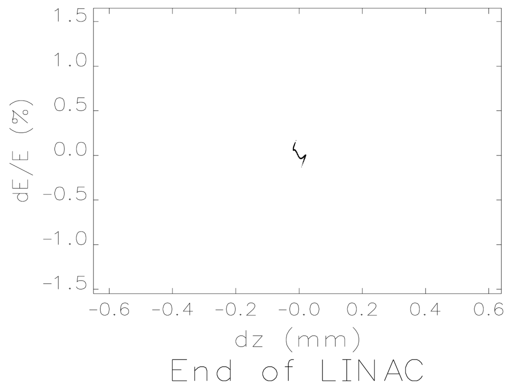
E = 5847 MeV, σ_δ = 0.039%
σ_x = 25 μm, σ_y = 15 μm, σ_z = 9.2 μm
ε_{nx} ~ 0.463 μm, ε_{ny} ~ 0.346 μm
I_{peak} < 2.7 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 50.0 keV for |dz| ≤ 10 μm

Sven Reiche finished GENESIS simulation to design FEL beamlines by using output of this optimization-V !

Optimization-V Phase Spaces at 6 GeV







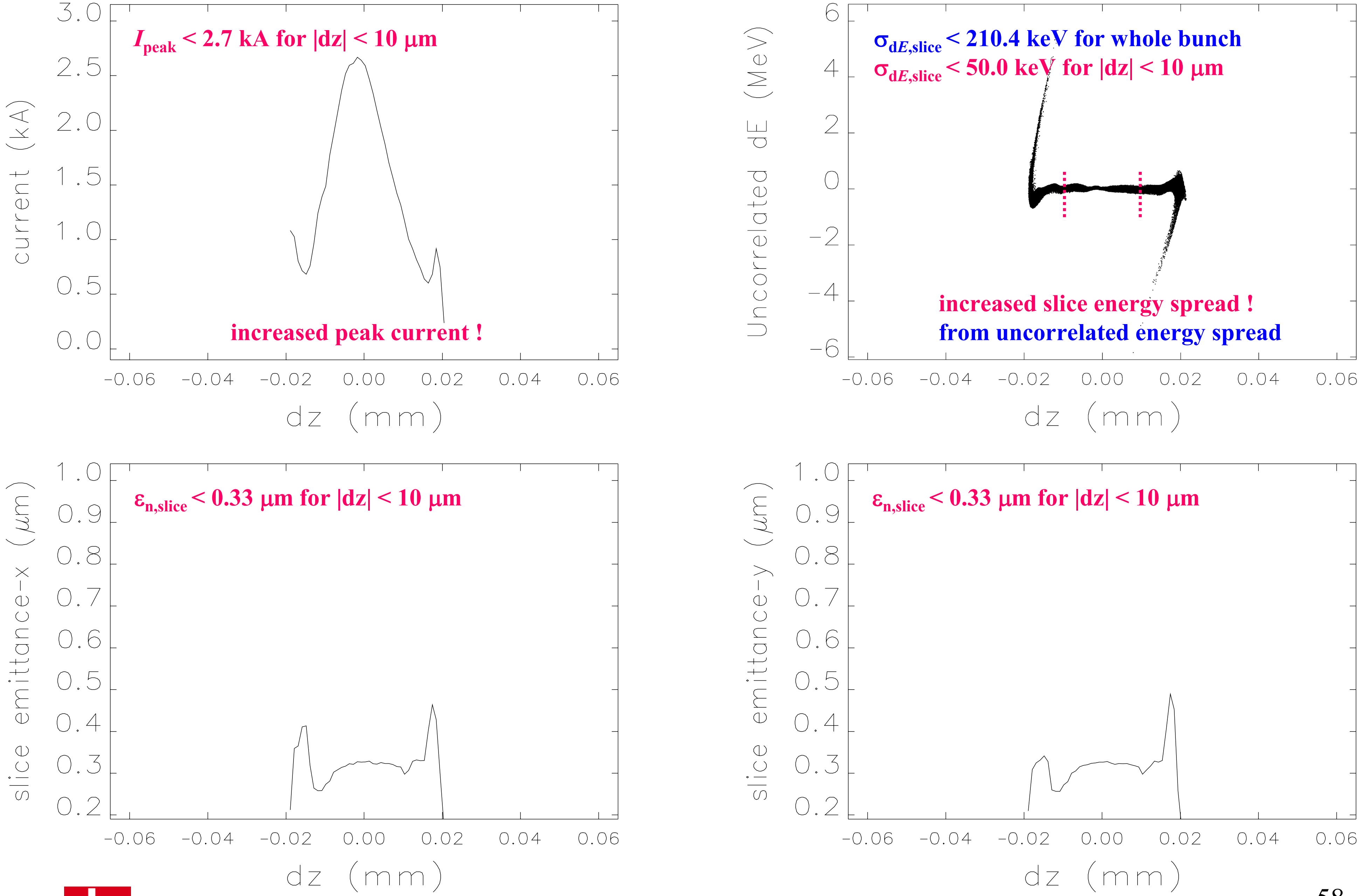
E = 6121 MeV, σ_δ = 0.033%

σ_x = 20 μm, σ_y = 20 μm, σ_z = 9.2 μm

ε_{nx} ~ 0.463 μm, ε_{ny} ~ 0.346 μm

I_{peak} < 2.7 kA, $\varepsilon_{n,slice}$ < 0.33 μm, $\sigma_{dE,slice}$ < 50.0 keV for |dz| ≤ 10 μm

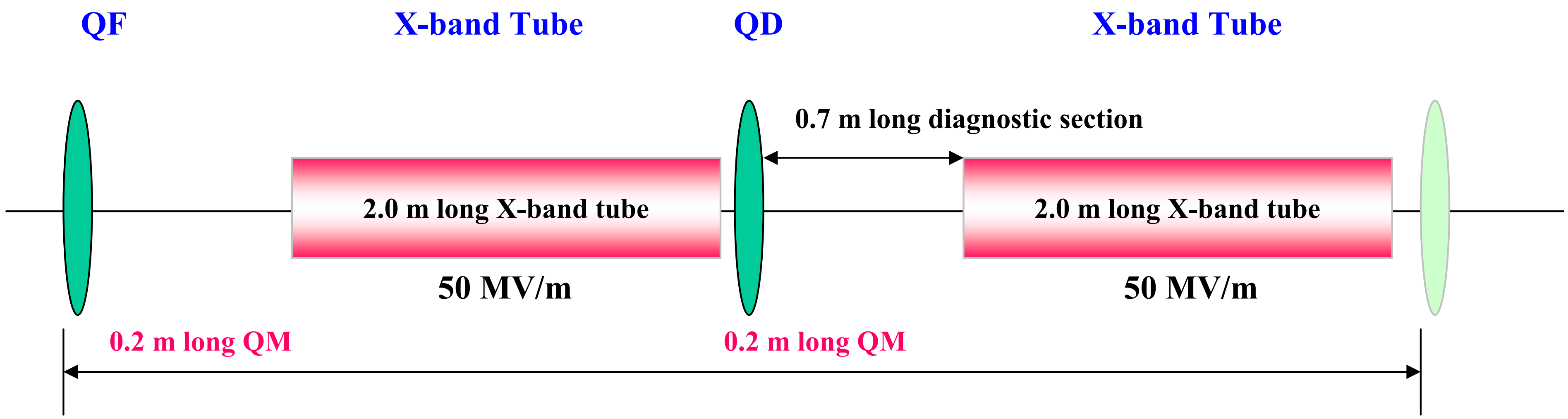
Optimization-V Slice Parameters at 6 GeV



1st Possible Solution to reduce LINAC2

PAUL SCHERRER INSTITUT

With PSI standard S-band layout, length of LINAC2 is 353.6 m !



One FODO Cell for LINAC2 = 5.8 m

Needed FODO cells ~ 30 cells

Needed X-band tubes ~ 60 tubes

Advantage = shortest linac (174 m) & possibility of the highest beam energy

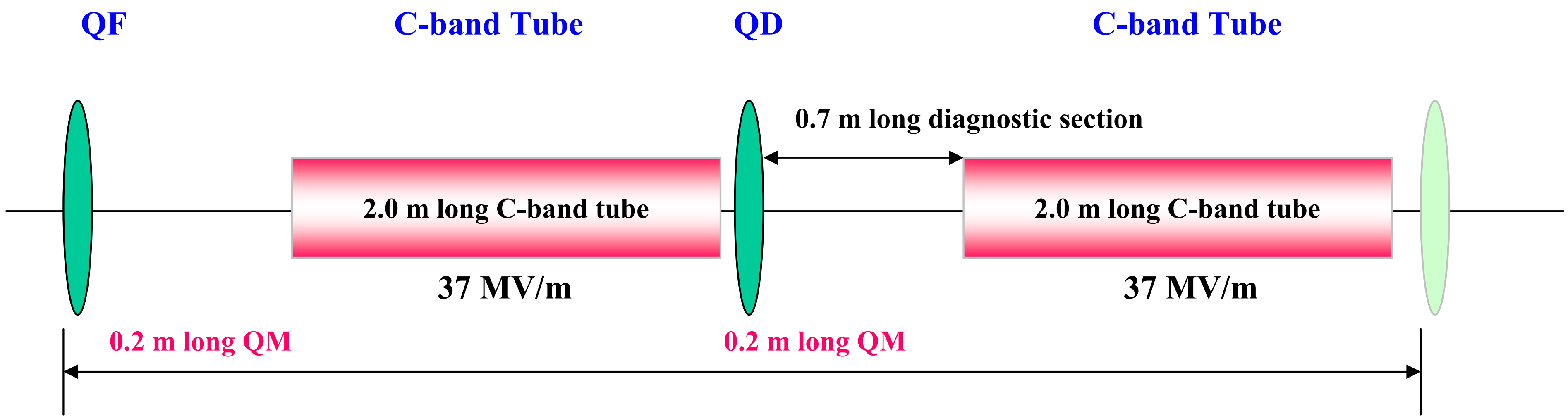
European X-band RF system is available and under developing at CERN for CLIC

Disadvantage = tightest RF tolerance

2nd Possible Solution to reduce LINAC2

PAUL SCHERRER INSTITUT

With PSI standard S-band layout, length of LINAC2 is 353.6 m !



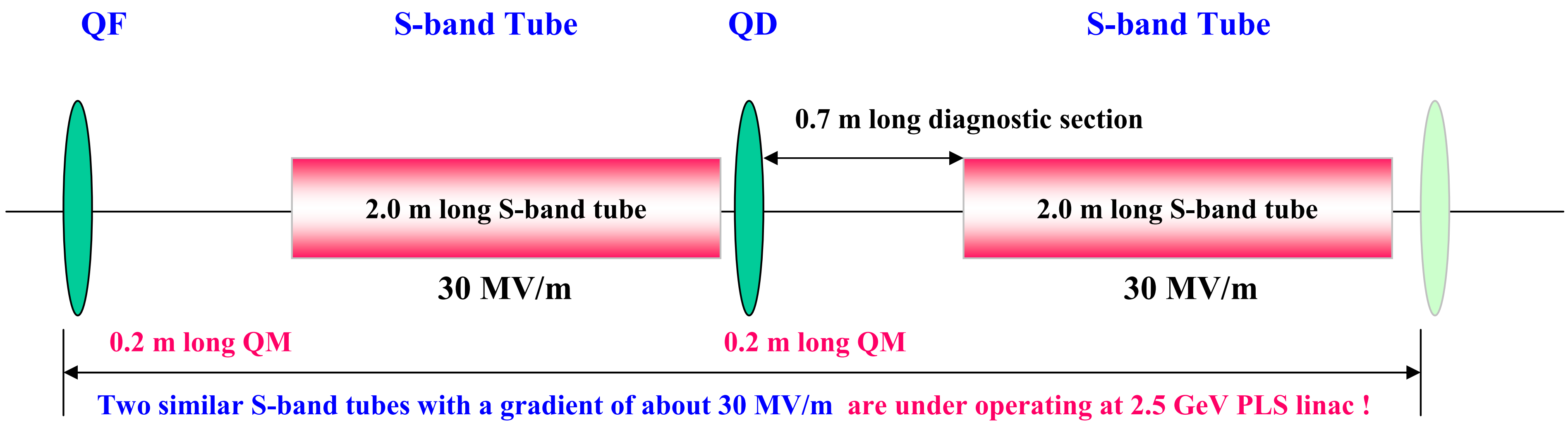
One FODO Cell for LINAC2 = 5.8 m
Needed FODO cells ~ 40 cells
Needed C-band tubes ~ 80 tubes
Advantage = shorter linac (232 m) & possibility of a higher beam energy
Disadvantage = effort to develop European C-band RF system & tighter RF tolerance

Can we change RF frequency from European frequency to American frequency ?

3rd Possible Solution to reduce LINAC2

PAUL SCHERRER INSTITUT PSI

With PSI standard S-band layout, length of LINAC2 is 353.6 m !



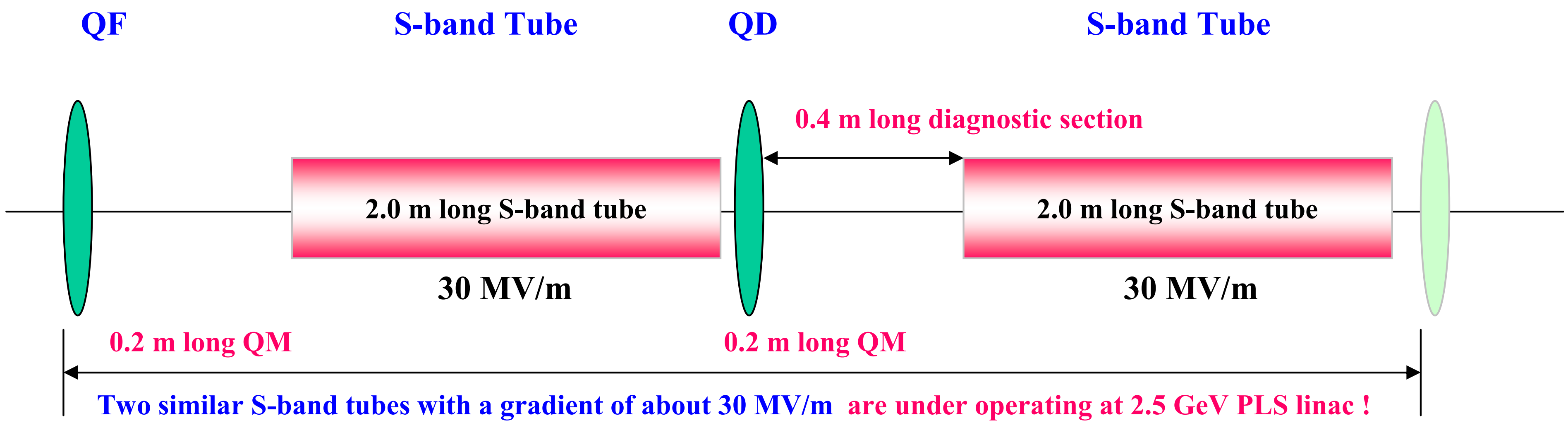
One FODO Cell for LINAC2 = 5.8 m
Needed FODO cells ~ 50 cells
Needed S-band tubes ~ 100 tubes
Advantage = shorter linac (290 m) & possibility of a higher beam energy
Disadvantage = effort to develop higher gradient S-band tube

KEK reached 40 MV/m with 2 m long S-band tube, and they can operate it for about 200 hours stably.
They used the high-pressure ultra-pure water rinsing technique (HPR) to remove dust particles in tube.
Y. Igarashi *et al*, Proc. in LINAC2002.

4th Possible Solution to reduce LINAC2

PAUL SCHERRER INSTITUT

With PSI standard S-band layout, length of LINAC2 is 353.6 m !



One FODO Cell for LINAC2 = 5.2 m
Needed FODO cells ~ 50 cells
Needed S-band tubes ~ 100 tubes
Advantage = shorter linac (260 m) & possibility of a higher beam energy
Total linac length < 500 m if we use this tubes in LINAC1 & LINAC2
Disadvantage = effort to develop higher gradient S-band tube

KEK reached 40 MV/m with 2 m long S-band tube, and they can operate it for about 200 hours stably. They used the high-pressure ultra-pure water rinsing technique (HPR) to remove dust particles in tube. Y. Igarashi *et al*, Proc. in LINAC2002.

Summary

After considering all key beam dilution effects such as space charge force at a low energy region, short-range wakefields in linac, Coherent Synchrotron Radiation (CSR) and Incoherent Synchrotron Radiation (ISR) in bunch compressors, and chromatic & fringe-field effects in magnets, we have performed the first full start-to-end simulations from the cathode to the end of 6 GeV linac with the CTF3 RF gun for the PSI-XFEL project.

We have optimized 250 MeV injector with the CTF3 RF gun, which was based on our realistic thermal emittance measurements with a copper cathode at OBLA.

Optimized 250 MeV injector supplies following promising beam parameters:

- **single bunch charge : 0.2 nC**
- **central core slice emittance ~ 0.32 μm**
- **maximum peak current before BC1 ~ 22 A**
- **maximum peak current after BC1 ~ 370 A**
- **projected emittance before BC1 ~ 0.35 μm**
- **projected emittance after BC1 ~ 0.38 μm**

Here assumed the thermal emittance on the cathode is 0.195 μm for σ_{laser} = 270 μm, ΔT_{laser} = 9.9 ps (FWHM).

Summary

We have optimized five different machine layouts giving following promising beam parameters at the end of 6 GeV PSI-XFEL Linac:

- single bunch charge : 0.2 nC
- central core slice emittance ~ 0.33 μm
- maximum peak current ~ 1.6 kA or 2.7 kA
- rms slice energy spread for whole bunch ~ 148 keV for 1.6 kA and 211 keV for 2.7 kA
- projected emittance ~ 0.40 μm for 1.6 kA and 0.46 μm for 2.7 kA

Here Optimization-I, II, and III supply I_{peak} ~ 1.6 kA and Optimization-IV and V supply I_{peak} ~ 2.7 kA.

In case of optimizations supplying I_{peak} ~ 1.6 kA (Optimization-I, II, and III), its peak current is somewhat low. But slice energy spread, projected energy spread and energy chirping, projected emittance are promising. Among them, Optimization-III supplies the best beam parameters.

In case of optimizations supplying I_{peak} ~ 2.7 kA (Optimization-IV and V), its peak current is high enough. But slice energy spread, projected energy spread and energy chirping, projected emittance are worse than those of I_{peak} ~ 1.6 kA cases. Among them, Optimization-V supplies the best beam parameters.

Summary

Just by re-tuning BC2, those two best optimizations (Optimization-III and V) can be operated without changing any machine components or layout.

S. Reiche already finished GENESIS simulations to design FEL beamlines by using output of Optimization-III and V.

It seems that we need a much longer linac (at least 650 m) to control energy chirping and energy spread properly, and to generate full coherent stable seeded XFEL photons (FEL3), and to generate the SASE based XFEL photons (FEL1 and FEL2) with a high intensity and a narrow bandwidth. We need deep studies to reduce length of LINAC2 with different RF frequency or tube.

To estimate energy chirping and needed linac length exactly, in the near future, we have to study the longitudinal short-range wakefields in the 4 m long S-band and 1 m long X-band linac structures deeply.

In the near future, dog-leg (DL), DIAG3 in DL, Switch Yards in LINAC2 will be designed. We expect that beam parameters will not be changed so much even though we include them in the linac.

Summary & Acknowledgements

With a different single bunch charge or peak current, we may control chirping of electron beams. Therefore, we need studies to get better slice parameters and the beam chirping with a lower single bunch charge.

To estimate 3D CSR effects and 3D space charge forces in BC1 and BC2, we will performed another simulations with CSRtrack and 3D space charge codes in the near future. We expect that slice parameters will not be changed so much even though we consider those 3D effects in BC1 and BC2.

Just we started start-to-end simulations to find RF jitter tolerances and alignment tolerances in the 6 GeV PSI-XFEL linac.

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