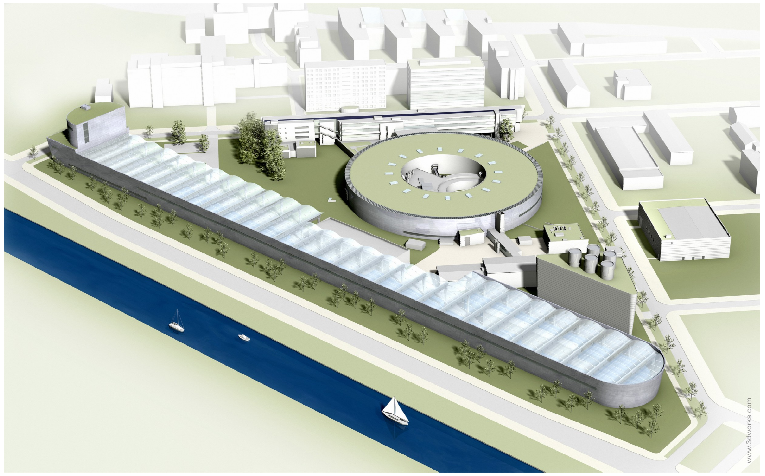
BESSY FEL:
Electron Optics & Bunch Compression

Michael Abo-Bakr



Outlook:

- **BESSY FEL: introduction**
- **Machine layout**
- **Bunch Compression & Linac Optics**
- **Tolerance Studies**

BESSY FEL characteristics/goals:

- **Soft-X-ray multi user facility**

- **4*th* generation high brightness snchrotron radiation source: $E_{phot,max} = 1$ keV ($\lambda_{min} = 1.24$ nm)**

- **CW operated 2.3 GeV linac**

- **multi stage HGHG: short pulses with highly reproducable wavelength, shape and intensity**

BESSY FEL characteristics/goals:

Photon energy range:	**25 eV to 1 keV (51 nm > λ > 1.2 nm)**
Time structure:	**< 20 fs**
Peak power:	**5 GW**
Pulse energy:	**100 μJ**
Pulse sequence:	**1 kHz macro-pulse (25 kHz SB)**
Brightness:	**10^{31} Ph./(sec mm^2 mrad^2 0.1%BW)**
No. FEL-line	**3**
No beamlines per FEL-line	**3 (5)**

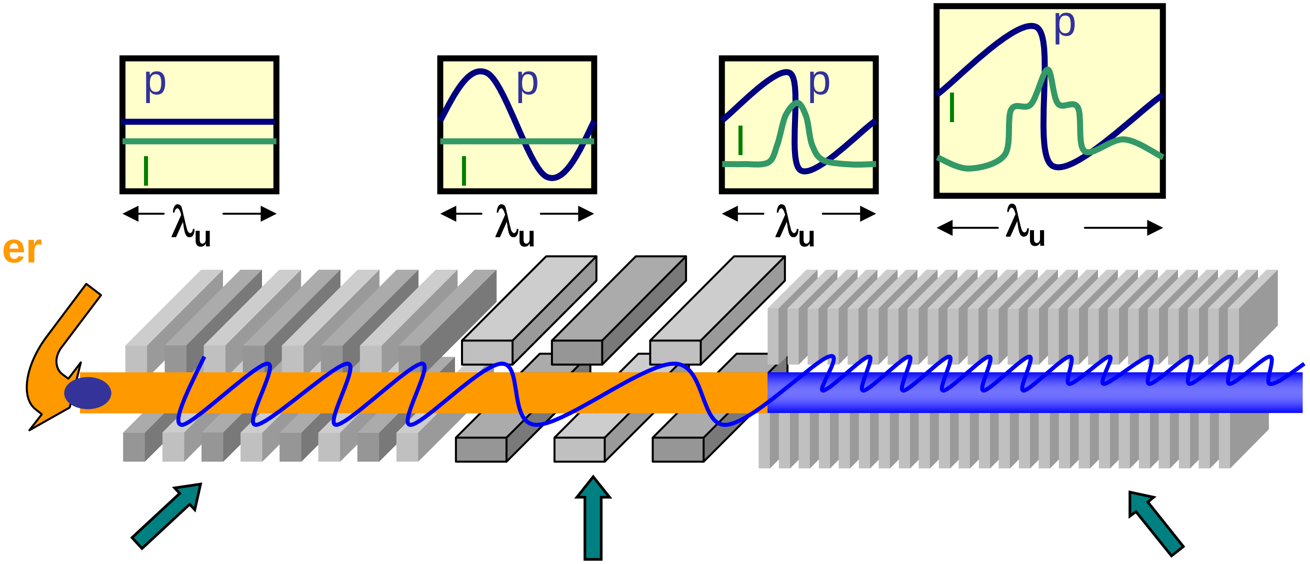
free selectable photon beam polarization

fully coherent photon beams

High Gain Harmonic Generation (HGHG)* Principle

High power fs-laser (Ti:Sa-variable frequency)

intense high brilliant e$^-$ beam



Modulator:

External seed at ω_o overlaps electron beam, modulating beam energy.

Dispersive Section:

Energy modulation is causing a spatial bunching in chicane magnets.

Radiator:

Electron beam radiates coherently at $h \cdot \omega_o$ in long radiator, tuned in resonance to harmonic $h = 3$ ..5.

DUVFEL

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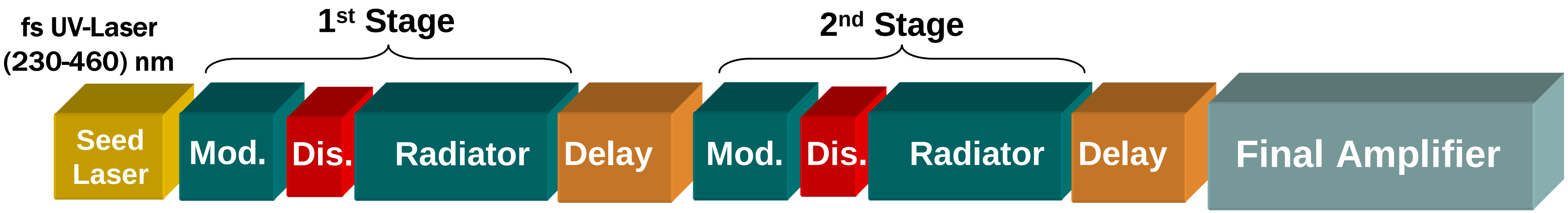
*Developed and demonstrated by L.-H. Yu et al.

High Gain Harmonic Generation (HGHG) Principle

radiator output → seeding radiation for the next stage

→ Cascaded HGHG scheme



fs UV-Laser
(230-460) nm

1st Stage

2nd Stage

Seed Laser

Mod.

Dis.

Radiator

Delay

Mod.

Dis.

Radiator

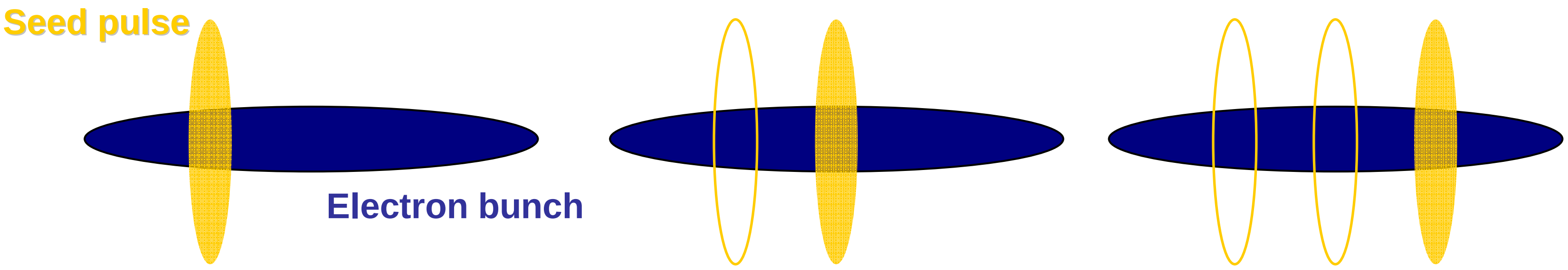
Delay

Final Amplifier

BESSY Soft X-ray “low energy” FEL-line

Electron beam quality degrades due to seeding and FEL amplification

→ “Fresh bunch” technique

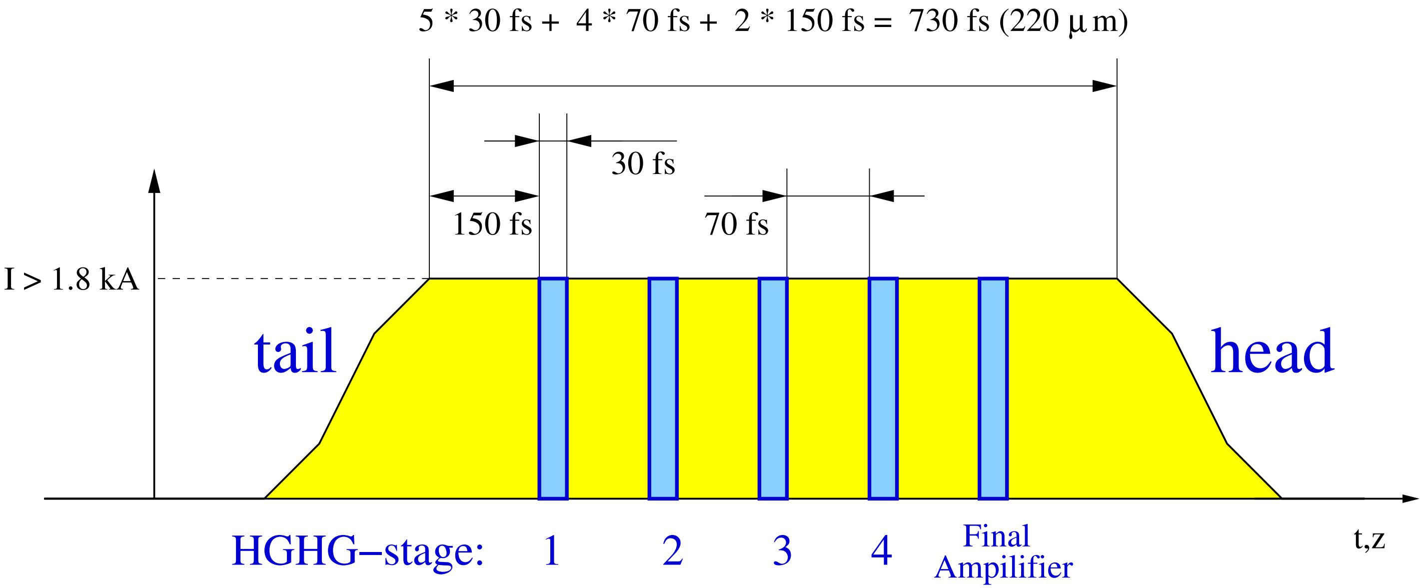


Seed pulse

Electron bunch

BESSY FEL: Electron Beam Requirements

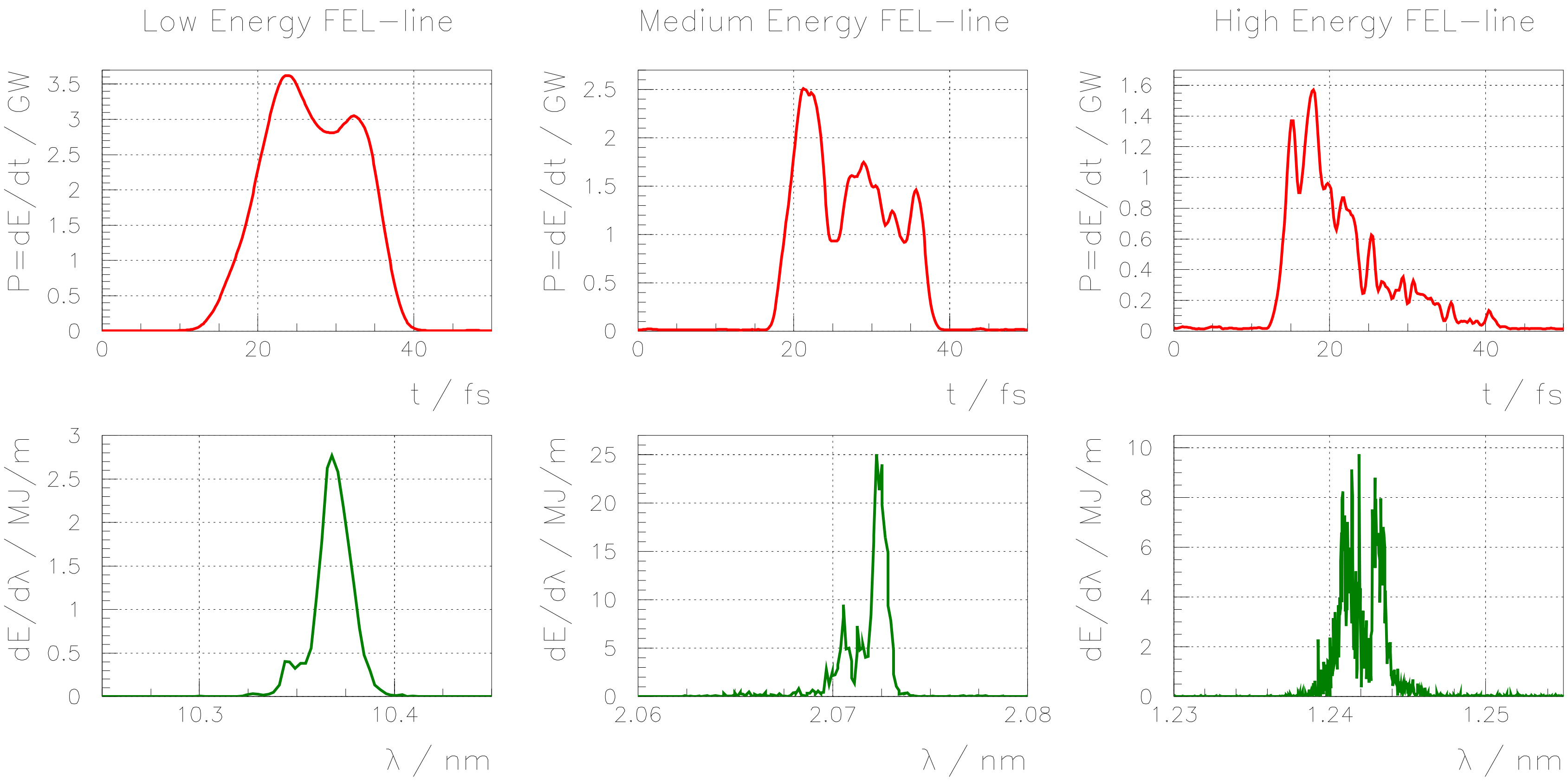
HGHG & ‘Fresh bunch’ technique: most challenging requirements from high-energy FEL line (4 stages)



Bunch Charge	**2.5 nC**
Electron energy	**2.3 GeV**
Peak current	**1.8 kA**
Transverse emittance*	**~ 1.5 π mm mrad**
Energy spread**	**1.0×10^{-4}**

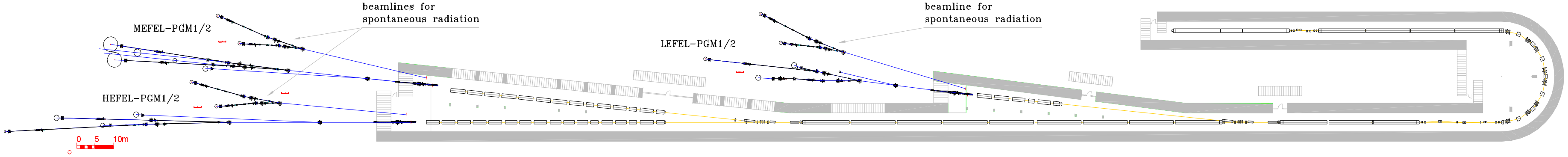
*** sliced, normalized**
**** sliced, relative**

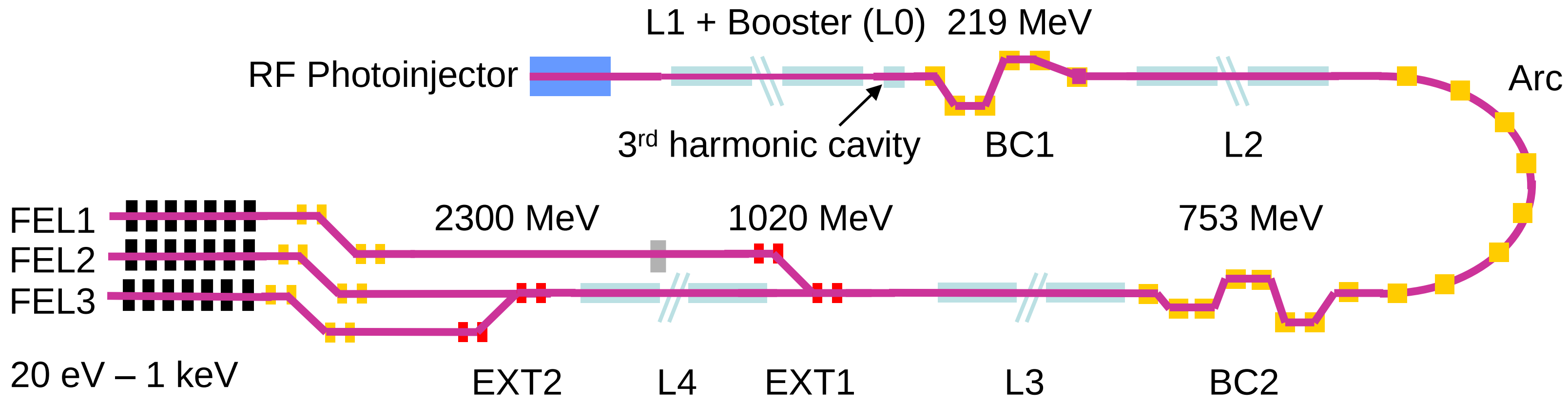
FEL Performance from Start-to-End Simulations



External Seed: variable Ti:Sa 460 – 230 nm, 500 MW,
Profile: Gauss, 17 fs (FWHM)

General Machine Layout





L1 + Booster (L0) 219 MeV

RF Photoinjector

Arc

3rd harmonic cavity

BC1

L2

FEL1

FEL2

FEL3

2300 MeV

1020 MeV

753 MeV

20 eV – 1 keV

EXT2

L4

EXT1

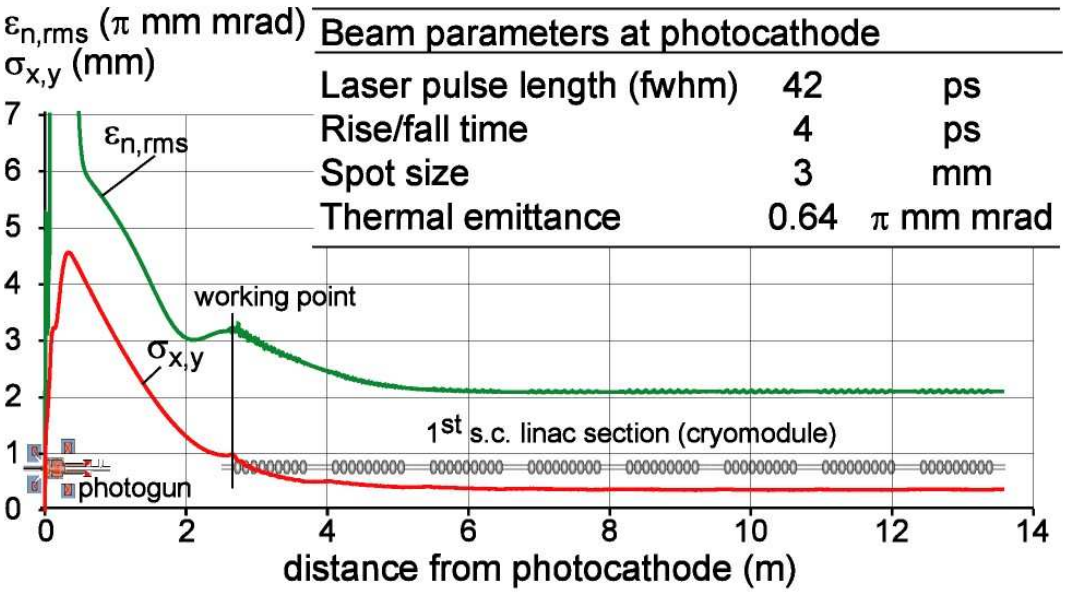
L3

BC2

- **nc pulsed photo-injector (PITZ design), later sc CW gun**
- **18 TESLA type modules with 8 cavities each = 144 cavities, average accelerating field: 16 MV/m, 3rd harmonic cavity required**
- **3 undulator section (FEL lines): 20/45/50 m**

Electron optics

gun simulations using ASTRA :



Beam parameters at photocathode		
Laser pulse length (fwhm)	42	ps
Rise/fall time	4	ps
Spot size	3	mm
Thermal emittance	0.64	π mm mrad

PITZ type gun, optimized for 1 kHz operation
(40 Mv/m peak field, 3 MW peak power,
75 kW verage power)

linac optics and buch conpression using ELEGANT:

- **two bunch compressors**
- **180 degree arc**
- **extraction sections for low and middle energy FEL line, dogleg**
- **long. collimator**
- **dispersive sections in undulator section**

Bunch Compression: two stage compression

First compression stage:

- moderate compression (arc)
- energy: compromise between decreasing momentum chirp and space charge forces versus increasing R56 of compressor (reduced chirp) at higher energies

Arc:

- must be passed with sufficiently long bunch length/ low peak current to avoid CSR effects
- energy: compromise between decreased sensitivity againcst CSR effects and space gained versus increasing R56 of second compressor at higher energies
- tuned to roughly isochronous behaviour – natural R56 acts decompressing, chromaticity needs to be controlled

Second bunch compressor:

- energy: low to decrease R56 -> directly placed at the arc's end

general: weak & short bending magnets to reduce strength of CSR fields
small hor. betafunctions in compressor dipoles (H-funktion)

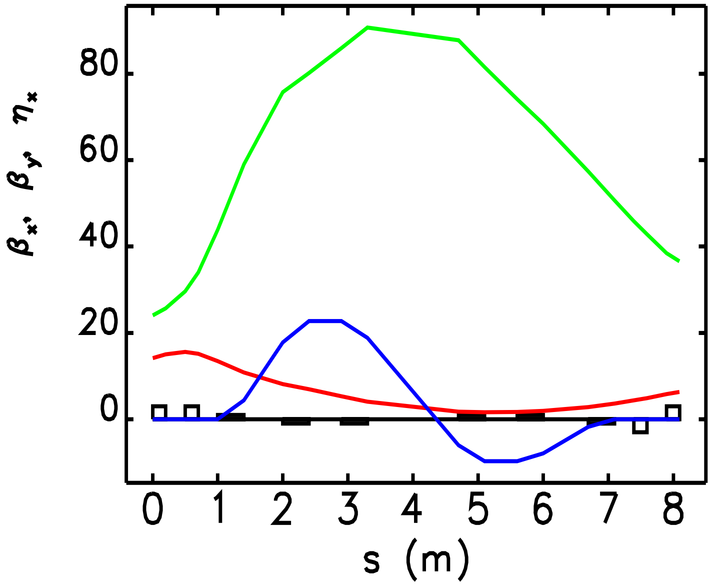
Bunch Compression

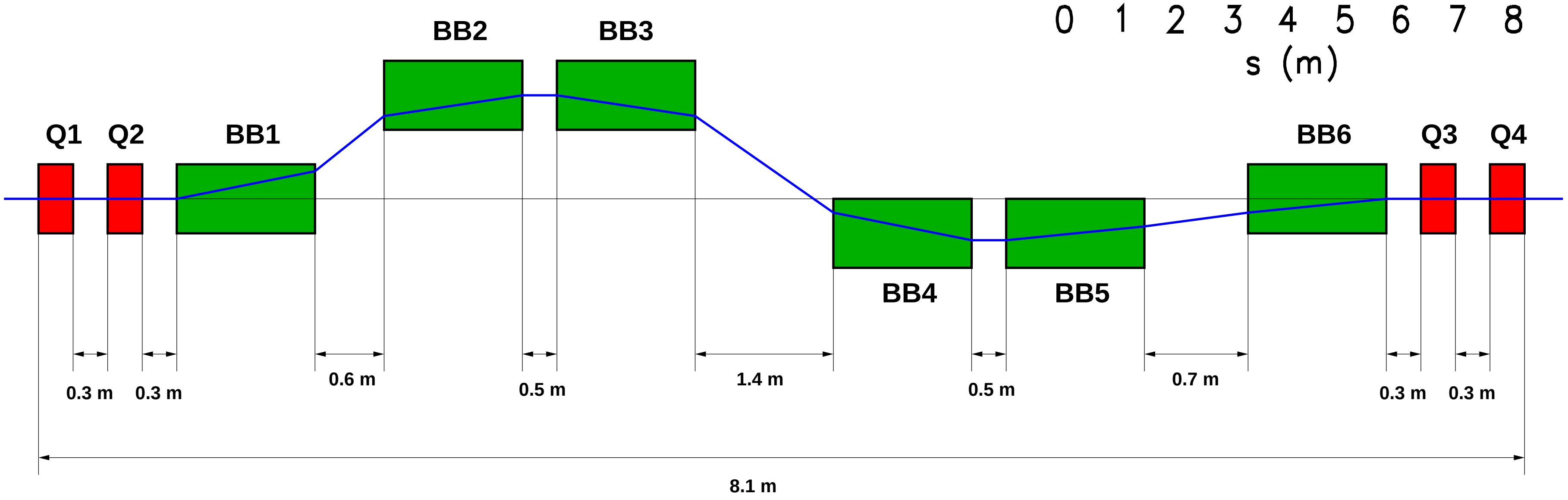
Two stage compression:

- start with long 60 A peak current pulse from injector
- chirp generated with “LINAC 1” (first two modules): ϕ = -13.3 degree, harmonic cavity slightly off crest
- BC1: R56 = -10.5 cm increasing peak current 60 A -> 200 A
- “Linac 2” still off crest by ϕ = -5.0 degree
- arc slighlty compressing: R56 = -1.9 cm 200 A -> 240 A
- BC2: R56 = -9.3 cm increasing peak current 240 A -> 1.8 kA
- downstream dispersive sections: no significant changes in bunchlength

Bunch Compressor 1

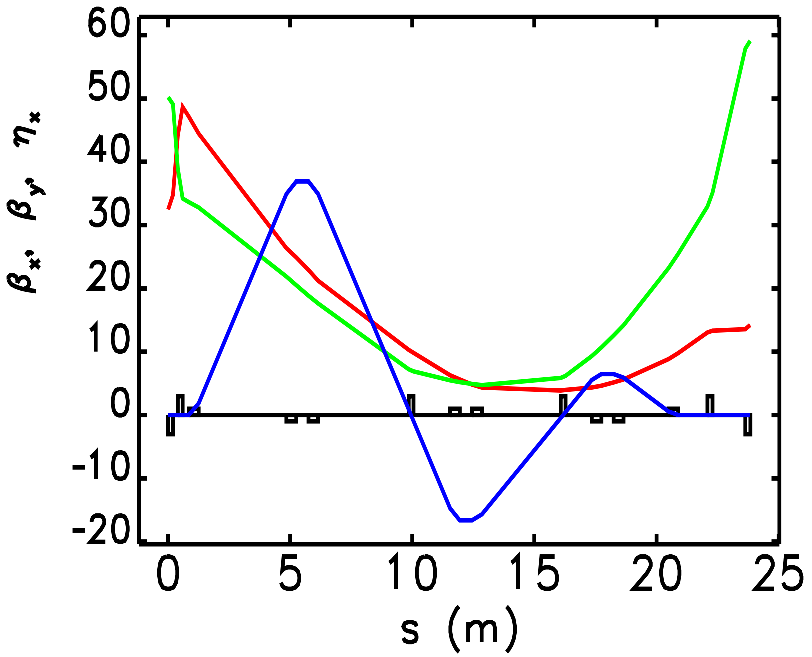
Type	*6 dipole chicane*
Energy	*219 MeV*
R_{56}	*-10.5 cm*
T_{566}	*16.4 cm*
Dipole length	*0.4 m*
Dipole bending radius	*1.80/2.25/4.50 m*
Dipole bending angle	*222/178/89 mrad*
Quadrupole length	*0.2 m*
Quadrupole strength	$< 3.0\ m^{-2}$

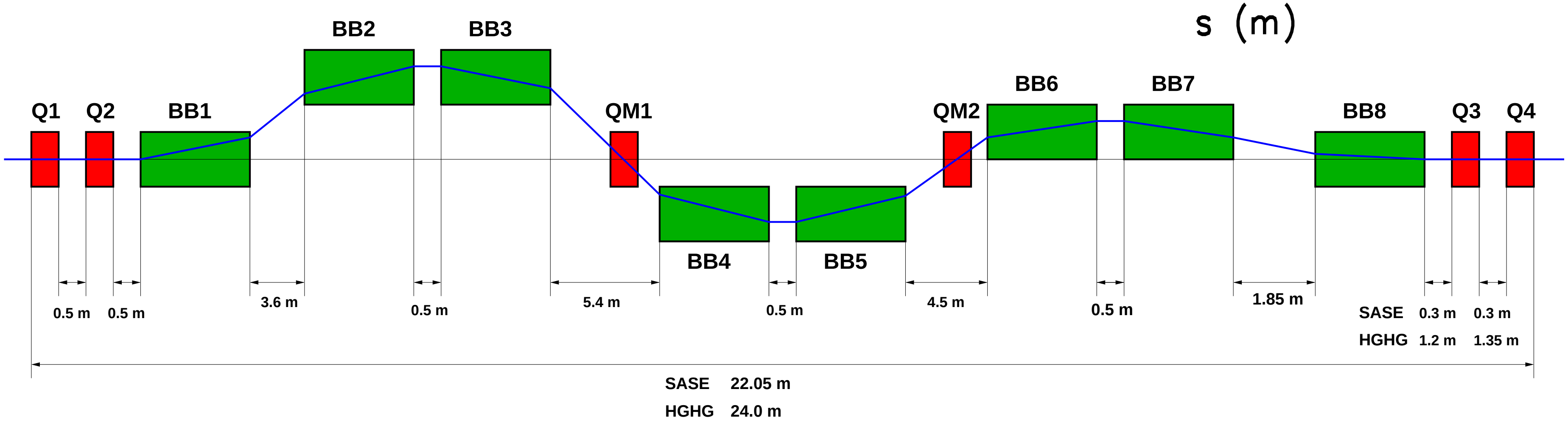




Bunch Compressor 2

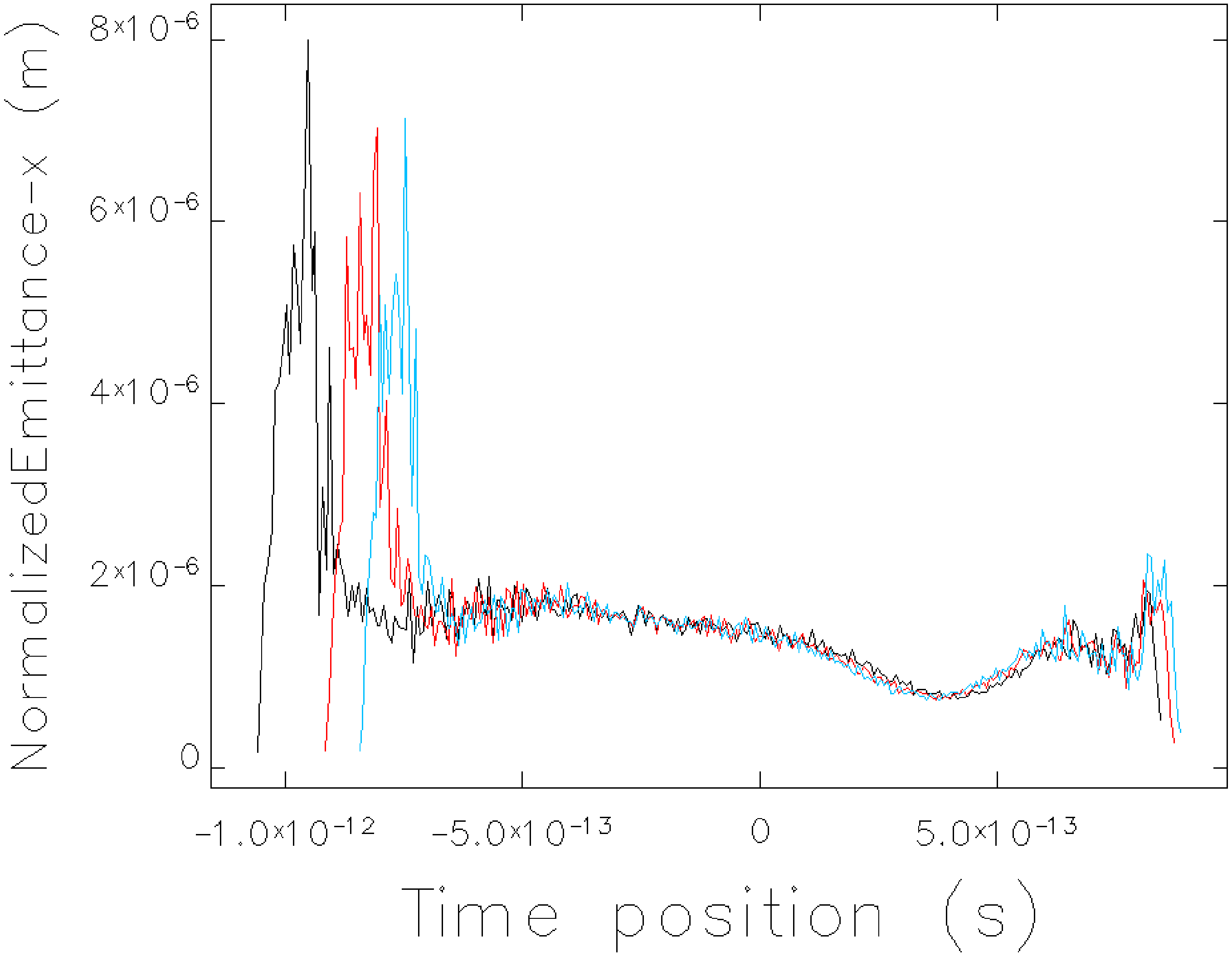
Type	*8 dipole chicane*
Energy	*753 MeV*
R_{56}	*-9.3 cm*
T_{566}	*14.0 cm*
Dipole length	*0.4 m*
Dipole bending radius	*4.36/8.50/13.89 m*
Dipole bending angle	*92/47/29 mrad*
Quadrupole length	*0.2 m*
Quadrupole strength	*< 5.0 m^{-2}*





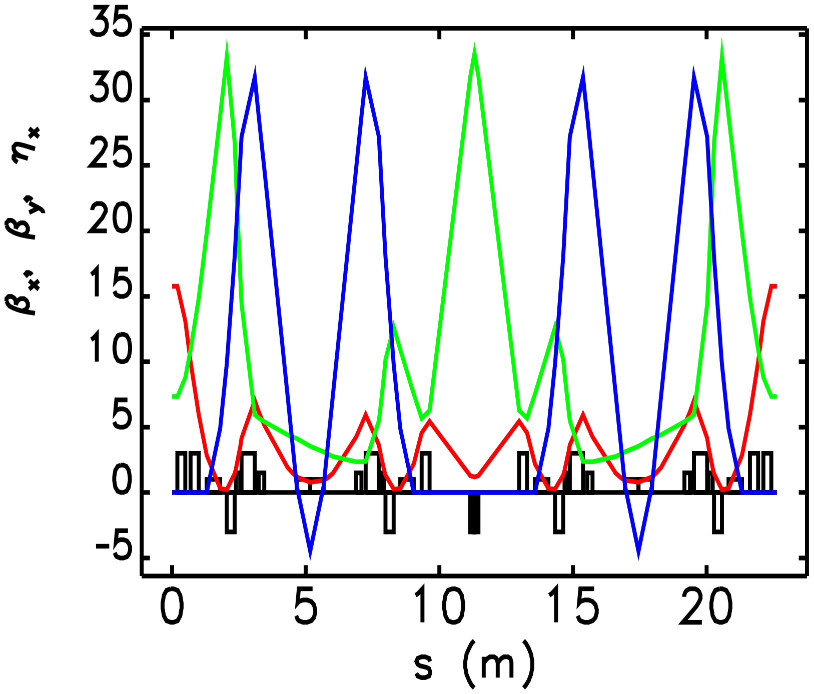
Bunch Compressor 2: charge variation

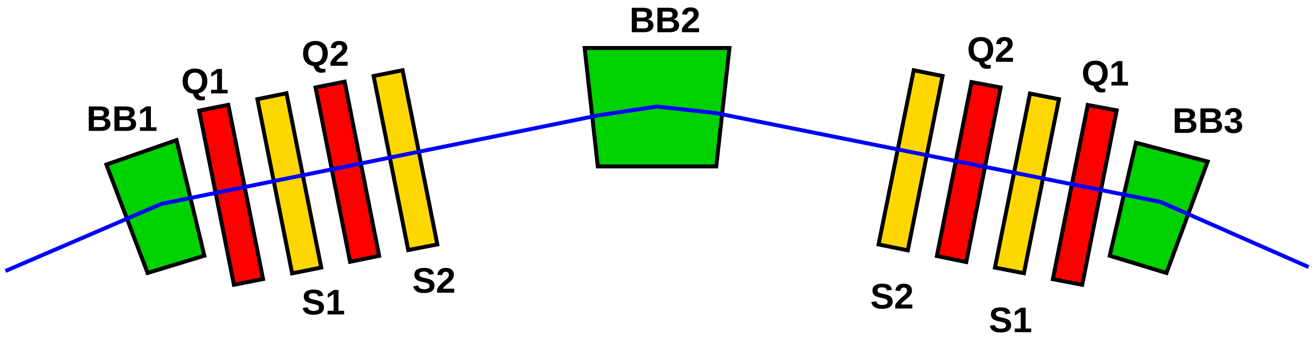
Sliced hor. Emittance through BC2 for 7.5 nC (black), 2.5 nC (red) and 0.1 nC (blue)



180 degree arc

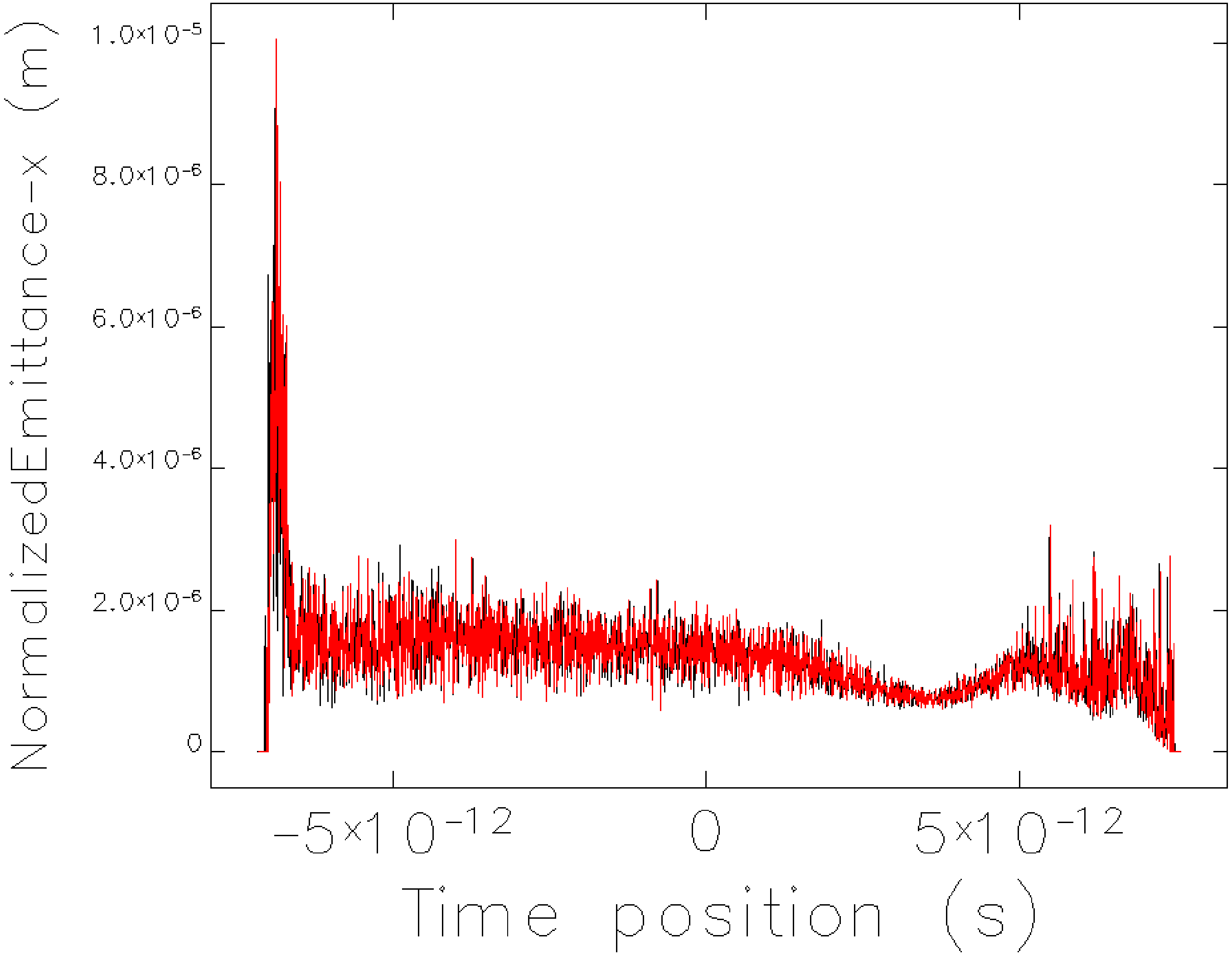
Type	*4 x 45°TBA*
Energy	*753 MeV*
R_{56}	*-1.87 cm*
T_{566}	*110 cm*
Dipole length	*0.5/1.0 m*
Dipole bending radius	*2.55 m*
Dipole bending angle	*196/392 mrad*
Total arc length	*48.4 m*
Arc diameter	*28.8 m*



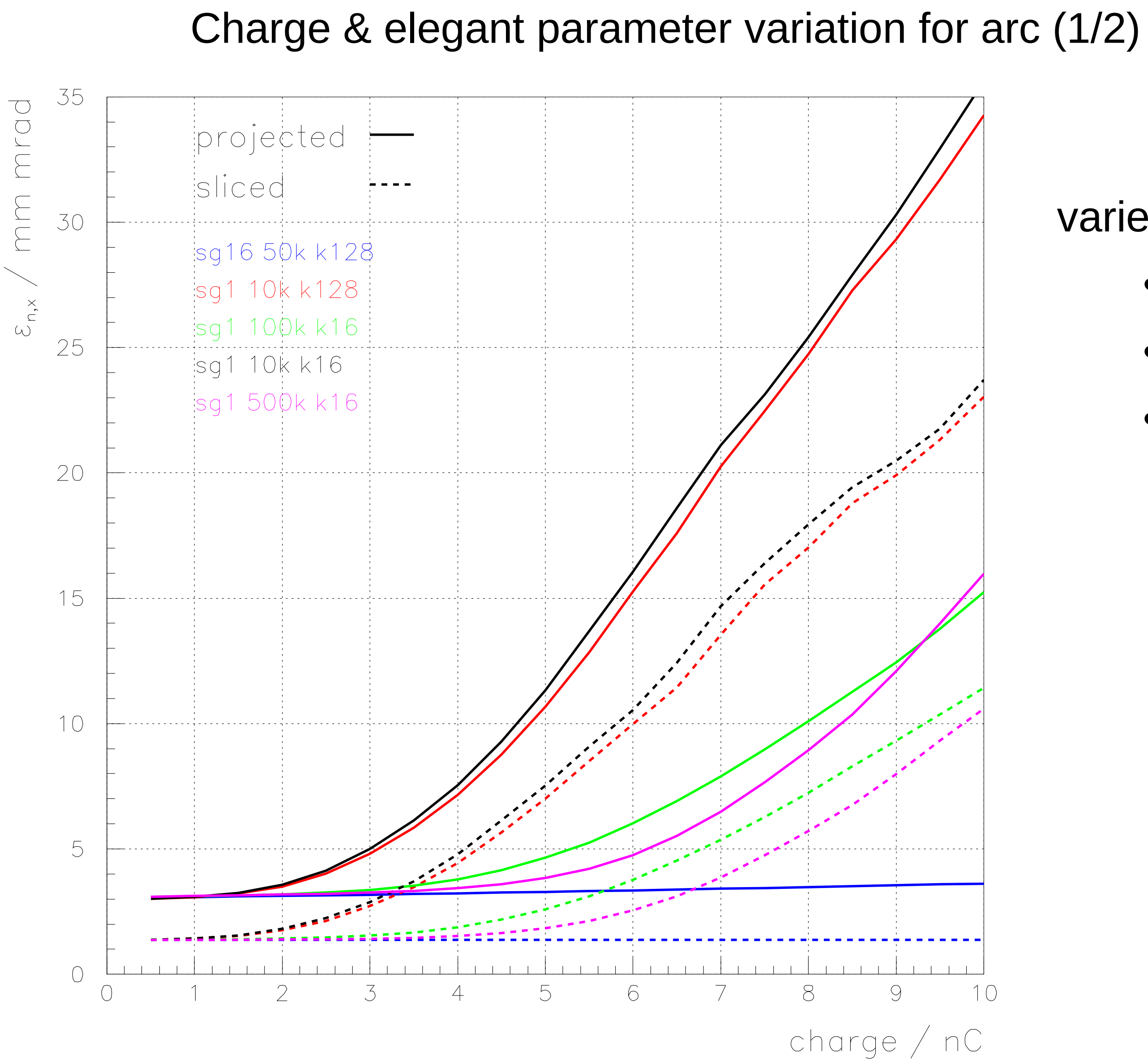


180 degree arc: charge variation

Sliced hor. Emittance through arc (1/2) for 2.5 and 7.5 nC (smoothing on)



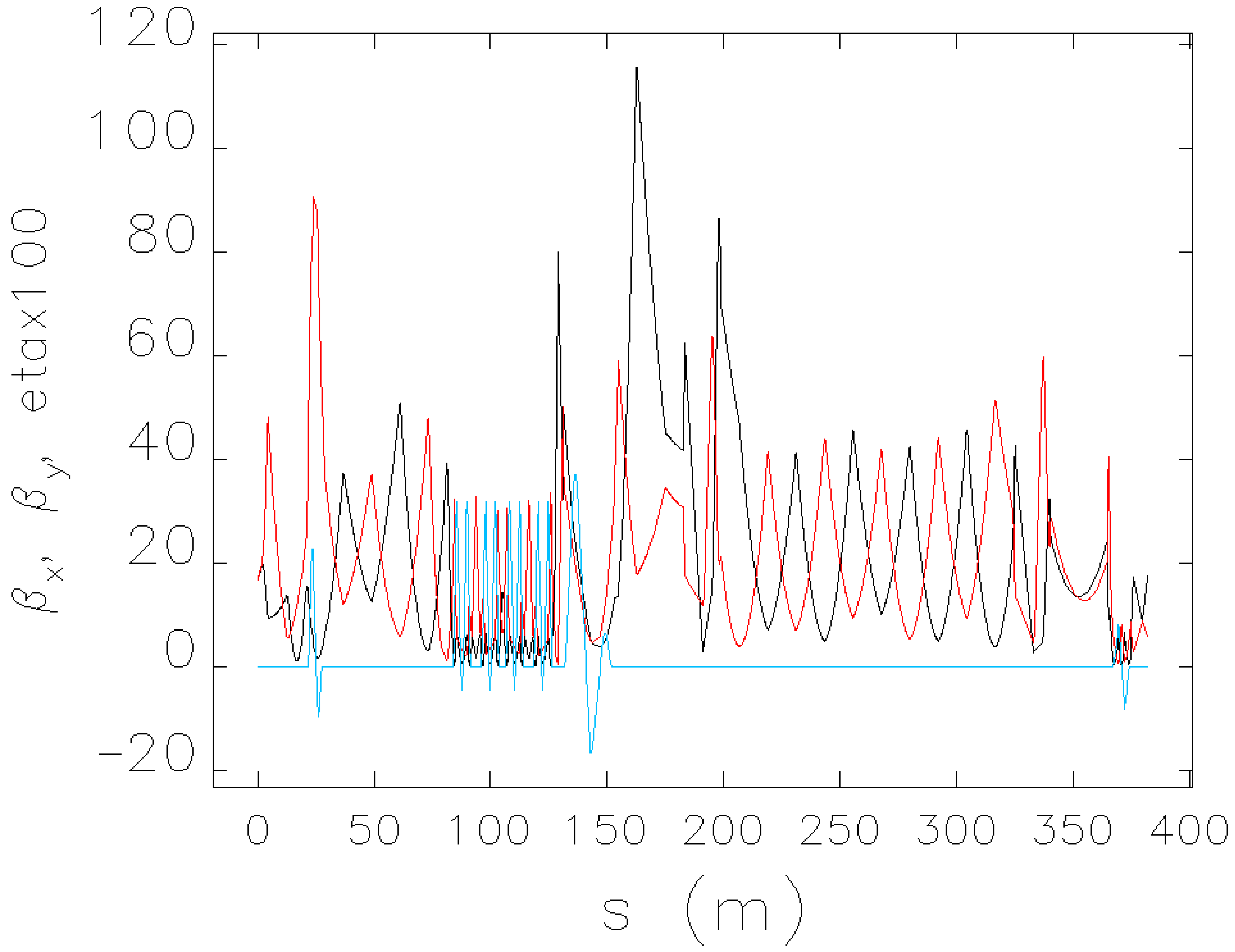
180 degree arc: charge variation


Charge & elegant parameter variation for arc (1/2)

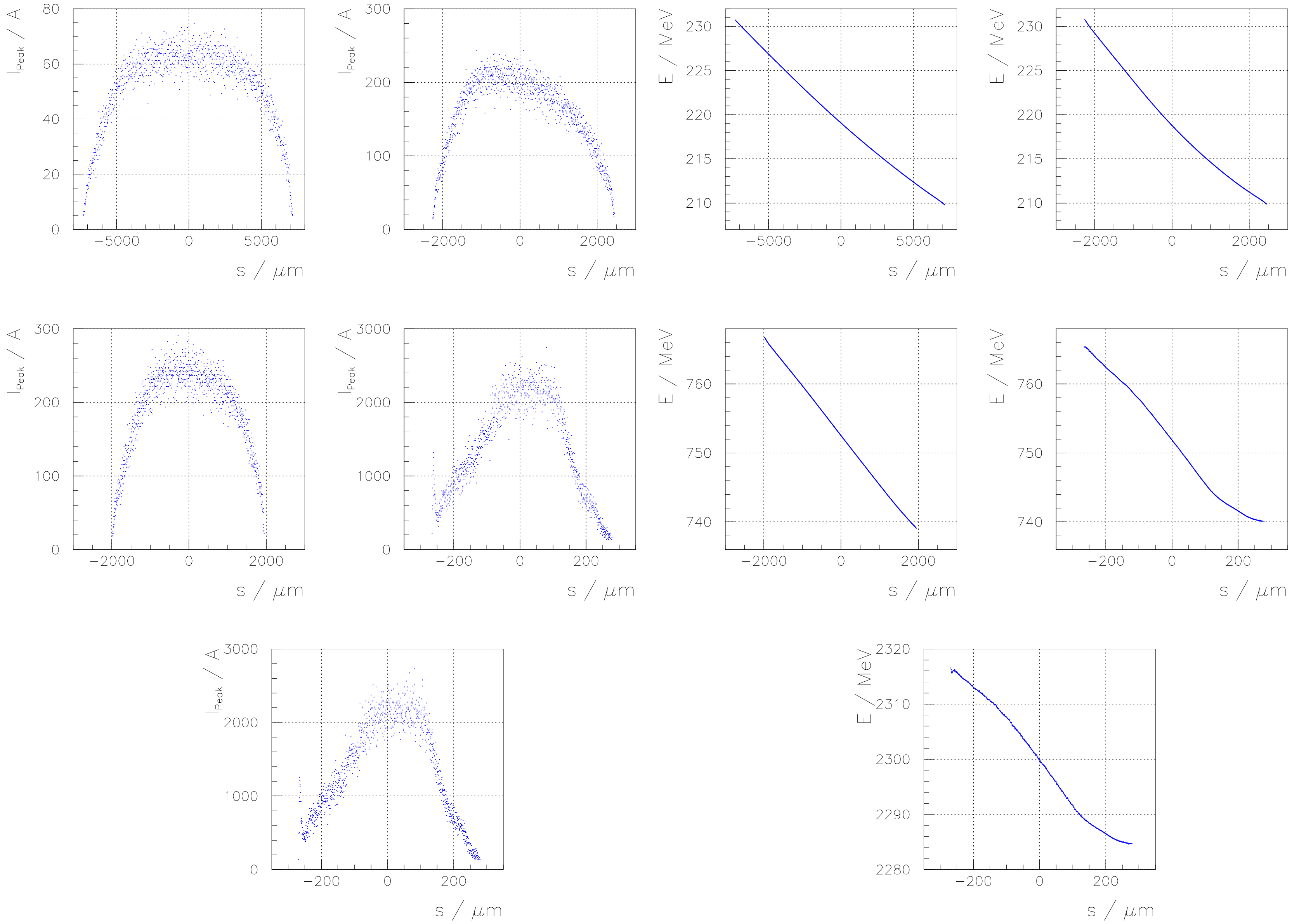
varied parameters:

- N_{part}
- N_{kicks}
- smoothing

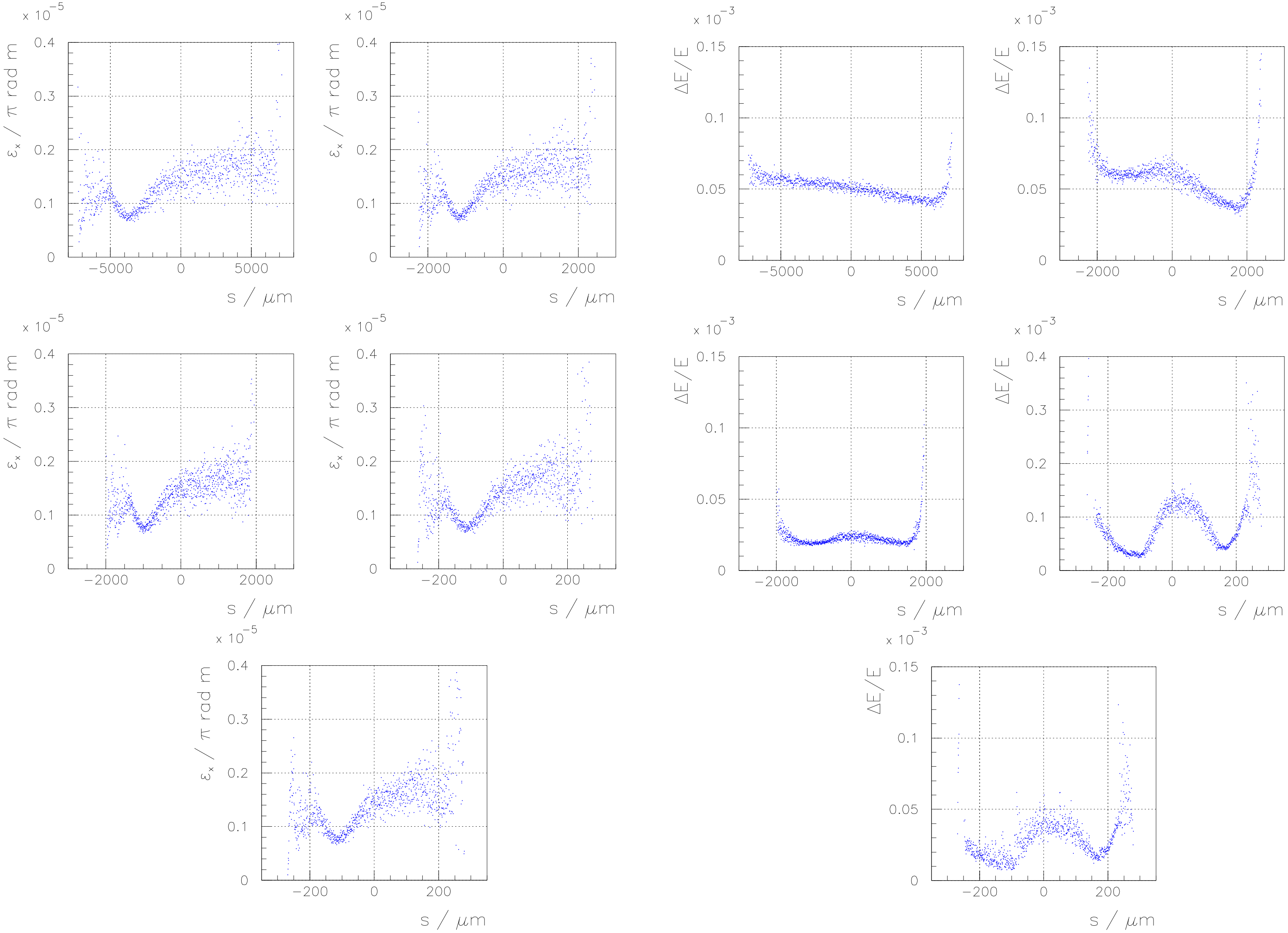
Full Linac: Twiss Parameters
(black = hor. beta, red = vert. beta, blue = hor. disp)



Linac Start-to End simulations: current distribution & long. phase space



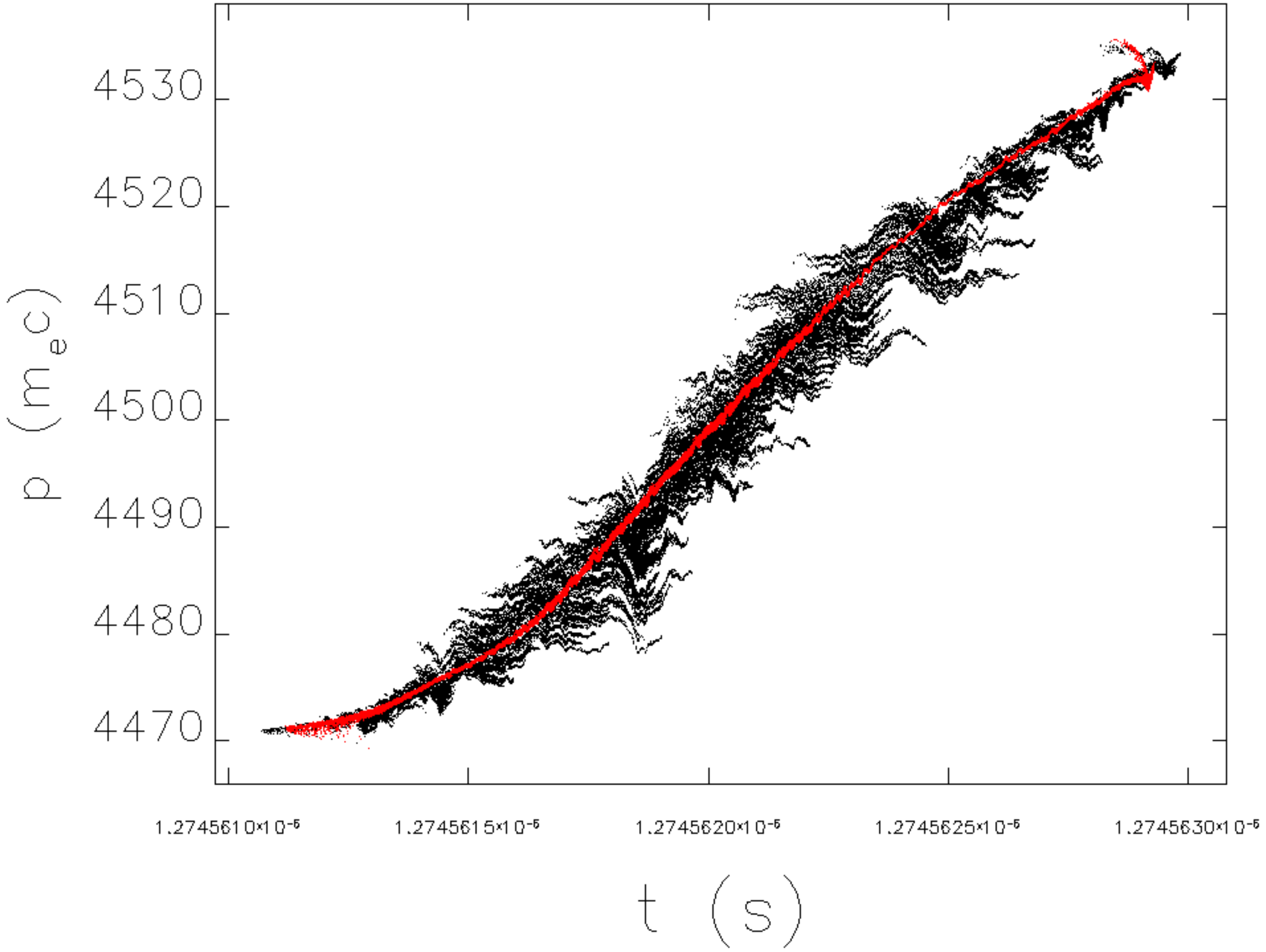
Linac Start-to End simulations: hor. emittance & energy spread



CSR microbunch instability ???: smoothing on/off

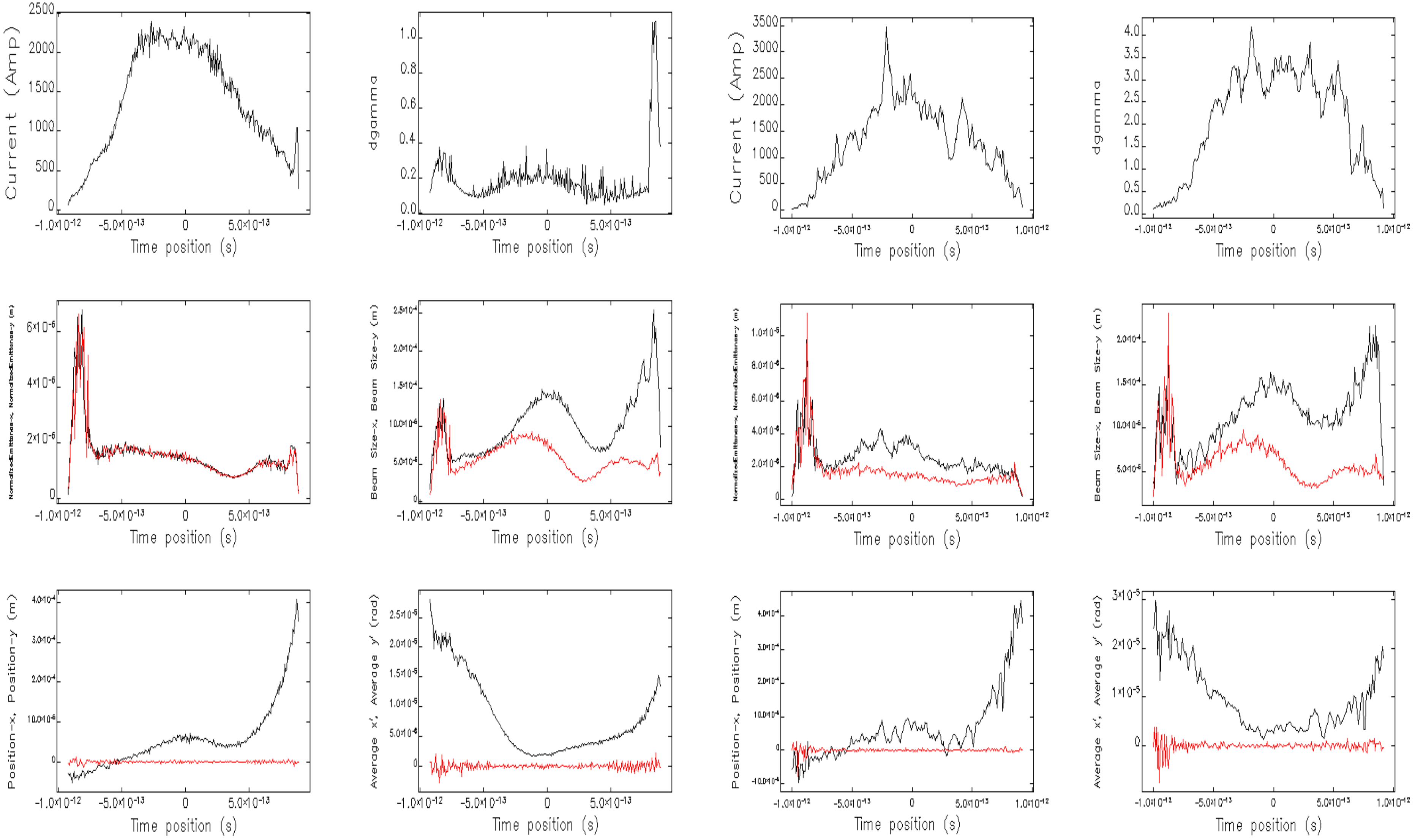
csr fields depends on dλ/ds -> stat. fluctuations can cause artificial dens. modulation

with (red, sg_hw=16, bins = 1000, 100k) and without (black) smoothing of charge density



CSR microbunch instability ???: smoothing on/off

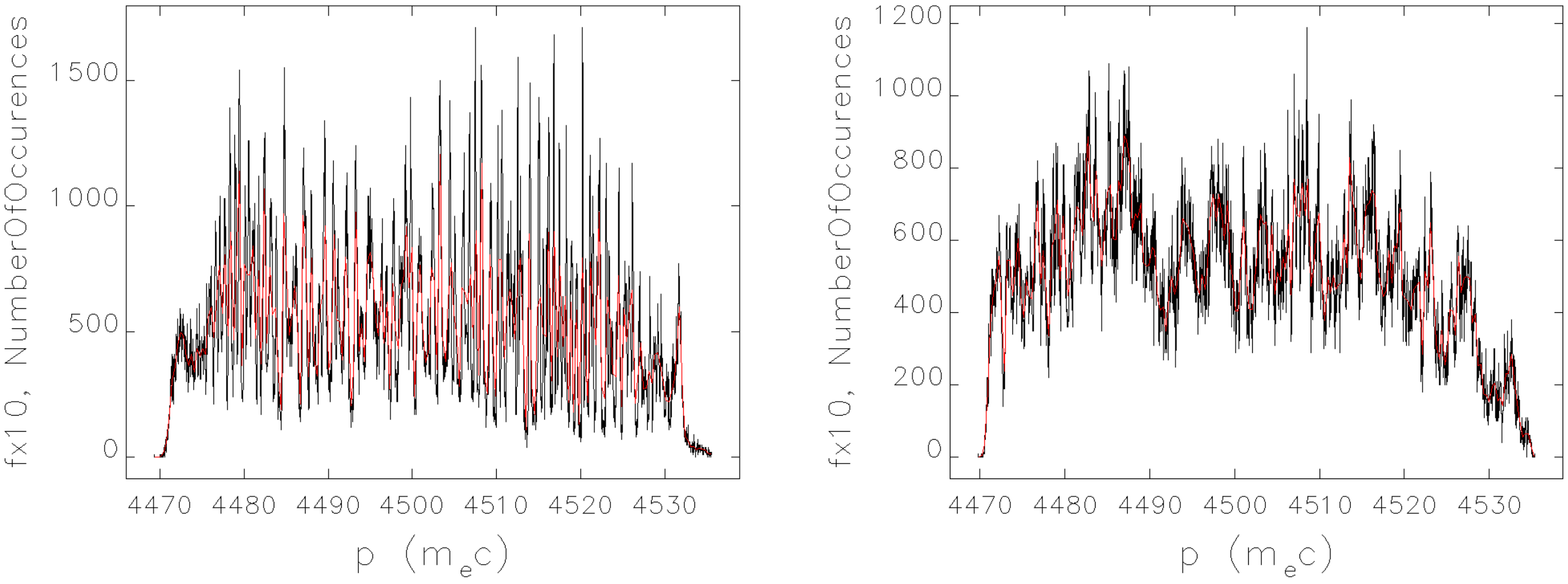
with (left, sg_hw=16, bins = 1000, 100k) and without (right) smoothing of charge density



CSR microbunch instability ???: smoothing on/off

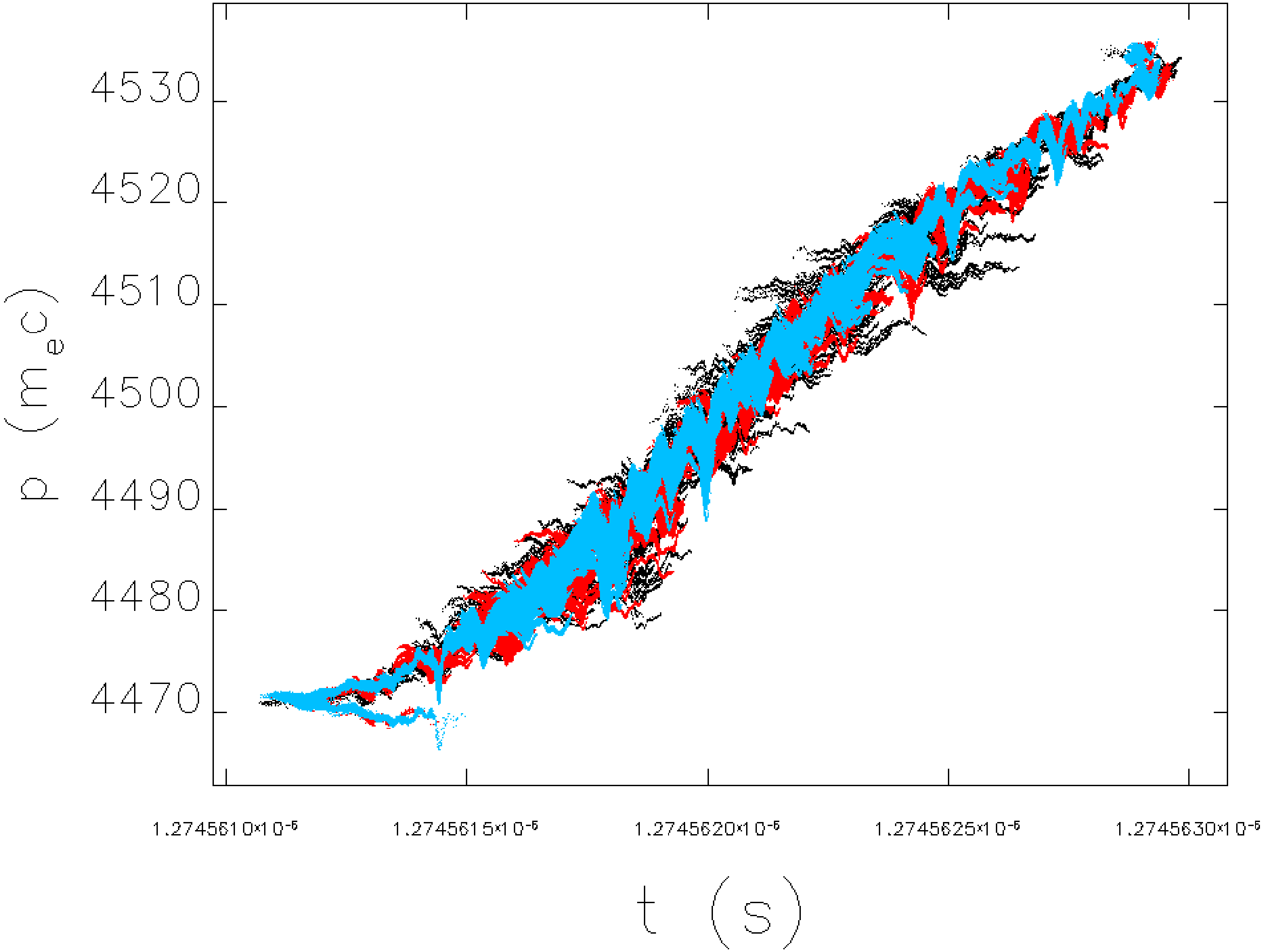
momentum distribution

with (left, sg_hw=16, bins = 1000, 100k) and without (right) smoothing of charge density
colors: histogram with 200 (red) and 2000 (black) bins, normalized



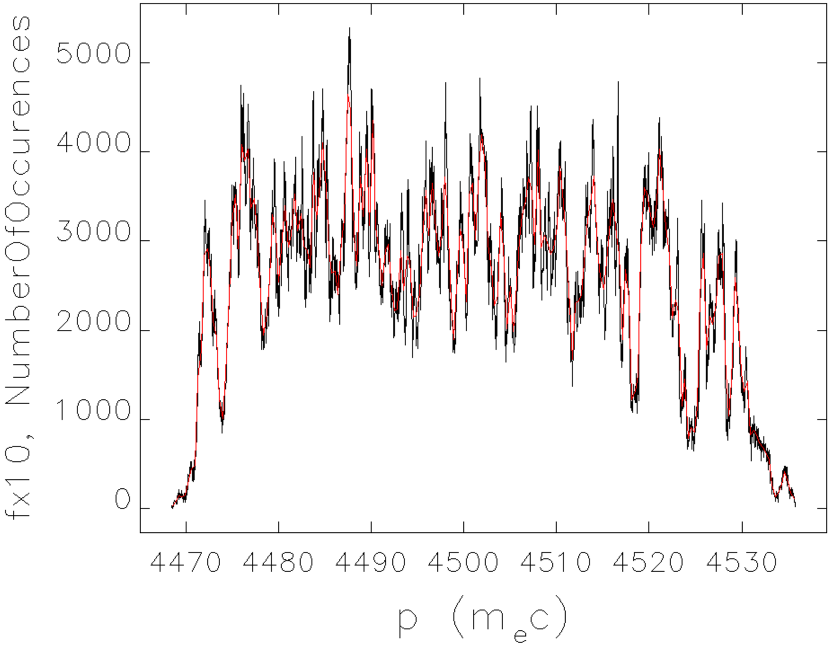
CSR microbunch instability ???

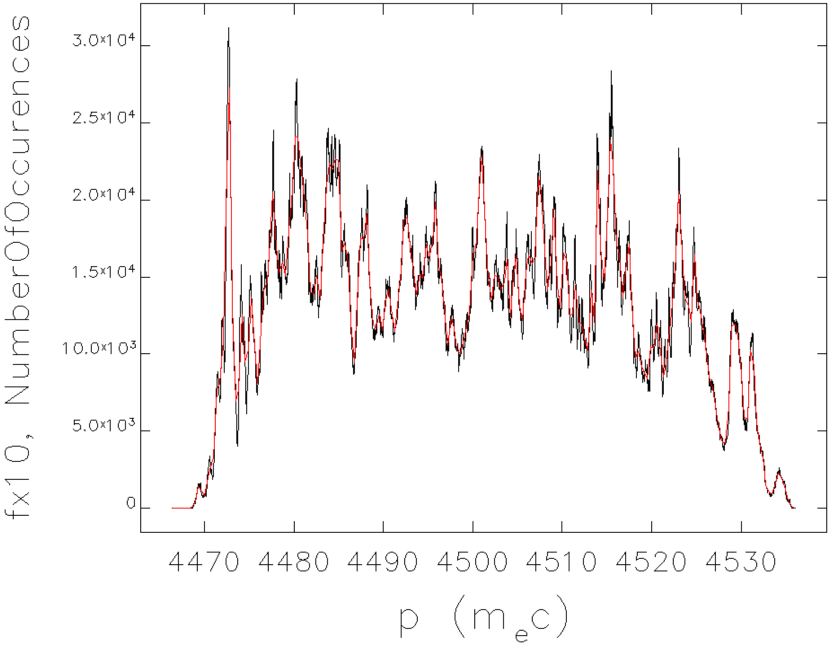
Long. Phase Space without smoothing: **dependency of the number of tracked particles**
(black: 100k = ref, red 500k, blue 2500k)



CSR microbunch instability ???

momentum distribution: **N_{part} dependency with no smoothing**
for 500k (left) and 2500k (right)





CSR microbunch instability: cure with laser heater ?

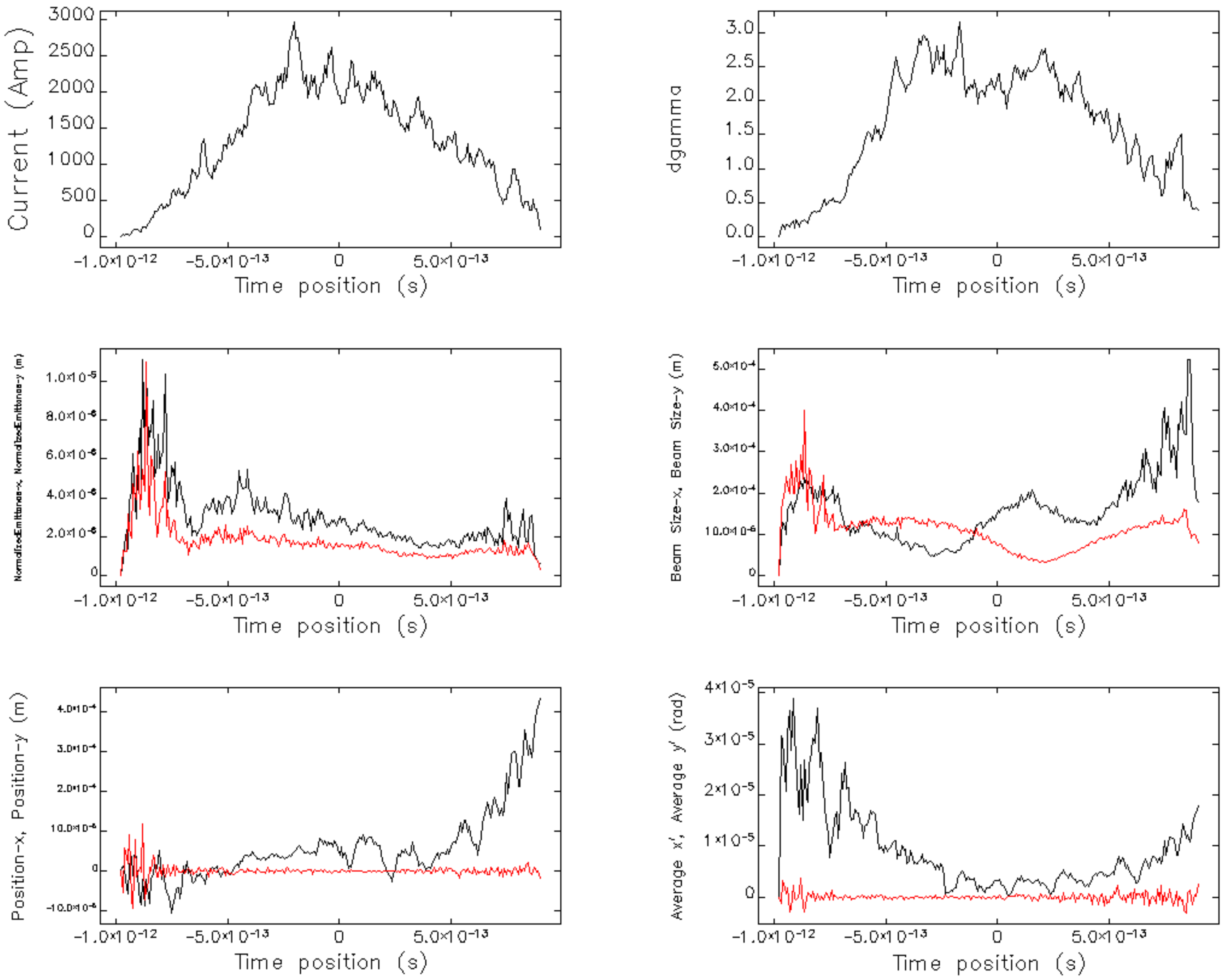
Laser Heater for (sliced) energy spread increase: does not fully solve the problem (N_{part})

Laser power:

300 kW

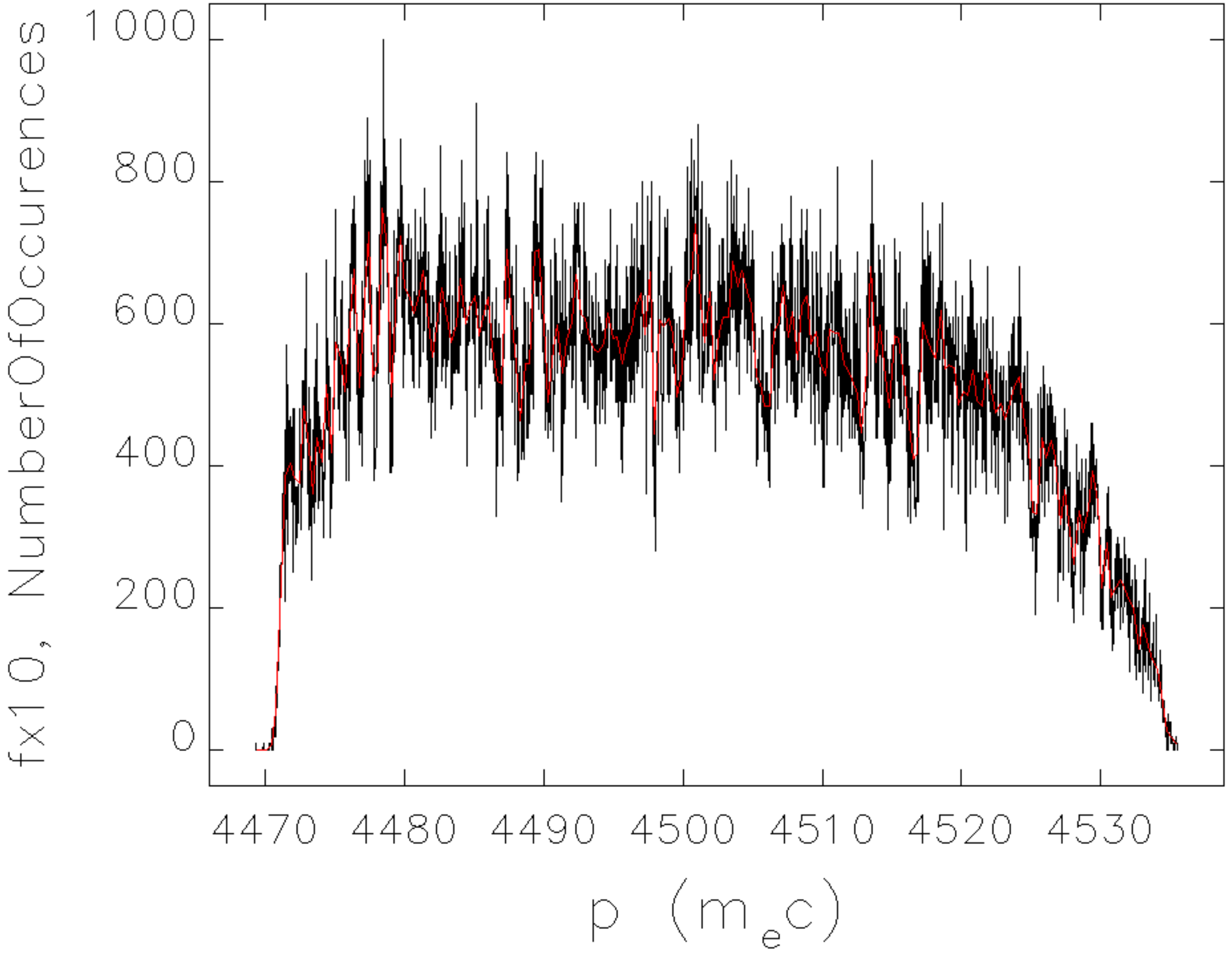
1.5 MW

60 MW



CSR microbunch instability: cure with laser heater ?

momentum distribution: with Laser heater (1500 kW)

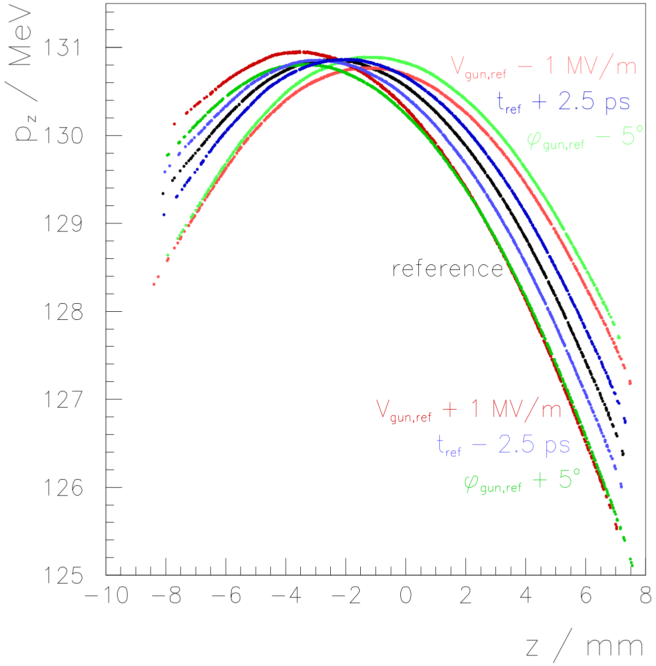


Tolerance studies

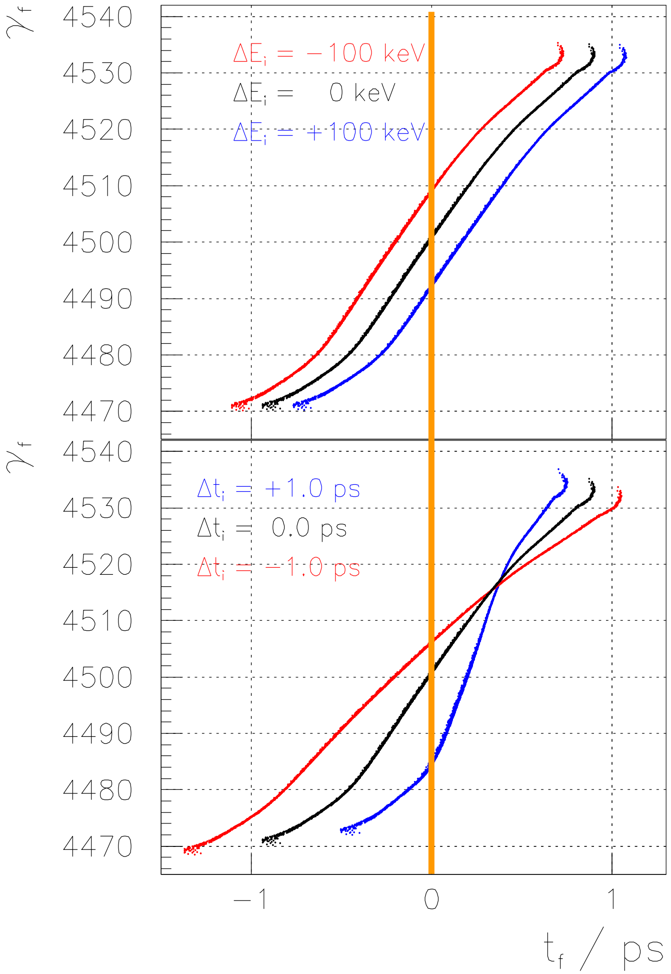
Most sensitive parameters:

energy spread (FEL's in general)

energy + arrival time (HGHG & seeding)



Single error injector simulations: long. phase space at booster module end for: ± 2.5 ps timing jitter (blue), ±1 MV/m gun amplitude (red) and ±5° gun phase errors (green), reference curve (black).



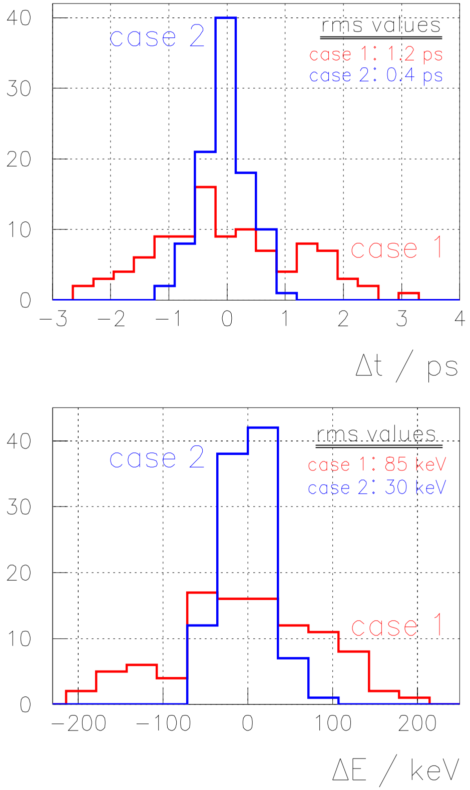
variations of final long. phase space (high energy beamline) due to energy (top) and timing (bottom) jitters from injector.

Tolerance studies

tolerance budget

		case 1	case 2
cath. laser	jitter / ps	0.5	0.25
	bunch charge (rel.)	1×10^{-2}	
injector gun	phase / °	1.0	0.2
	amplitude (rel.)	5×10^{-3}	2×10^{-3}
linac cav.	phase / °	0.1	
	amplitude (rel.)	3×10^{-4}	

Injector end (booster mod. end)



Linac end (begin of high energy FEL undulator section)