Linac optimisation for the New Light Source

- NLS source requirements
- Electron beam requirements for seeded cascade harmonic generation
- LINAC optimisation (2BC vs 3 BC)
  - CSR issues
  - energy chirp issues
  - jitter (preliminary studies at 200 pC and 500 pC)
- FEL simulations (time dependent SASE – cascade harmonic)

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Diamond Light Source and John Adams Institute, Oxford University

FEL Beam Dynamics Meeting

DESY, 13 July 2009

NLS Source requirements (Dec 08)

1. Photon energy range and tunability:
   Three FELs: FEL1 @ 50-300 eV; FEL2 @ 250-850 eV; FEL3 @ 430-1000 eV

2. Polarisation:
   FEL1&FEL2: complete polarisation control (arbitrary elliptical and rotatable linear).
   FEL3: at least horizontal and circular (R/L) polarisation over the full range 430-1000 eV.

3. Pulse length & pulse energy:
   20 fs FWHM photon pulse length at all photon energies with 10^{11} photons/pulse at 1 keV – (upgrade path to sub-fs pulses)

4. Repetition rate:
   1 kHz with an upgrade path to 100 kHz (or more)

5. Transverse and longitudinal coherence

Electron beam requirements

Operation of an X-ray FEL requires extremely high quality electron beams;

Energy	1-few GeV
Emittance (normalised)	10^{-6} m
relative energy spread	10^{-4}
Peak current	few kA

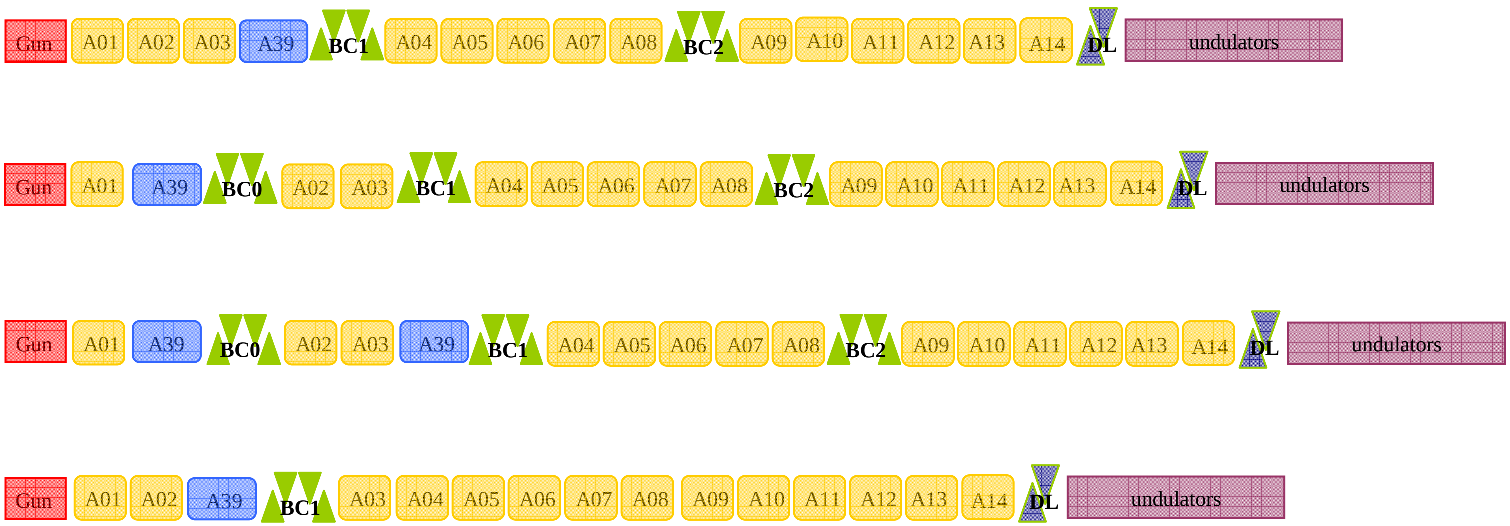
for seeded cascade harmonic generation

- constant slice parameters on a length of 100 fs – and more?
  - to accommodate the seed pulse and the jitters
  - without accidental good slices that would spoil the contrast ratio
- no jagged current distribution
- no slice offset and angle
- not too sensitive to jitters
- no residual energy chirp (or very limited)

Carefully optimised RF photocathode gun and LINAC with magnetic bunch compressors can provide high brightness electron beam, but satisfying all the requirements is non trivial

Layout and parameters of a 2.2 GeV Linac based FEL

- 2.2 GeV; 200-500 pC
- optimised L-band gun: 20 ps FW, 0.33 μm (proj. nor. emit.) → see J-H. Han's talk
- LINAC L-band gradient ~20 MV/m and 3HC @ 3.9 GHz ~15 MV/m
- Magnetic bunch compressors
- Beam spreader → see D. Angal-Kalinin's talk
- Undulator train → see also N. Thompson's talk on FEL harmonic schemes

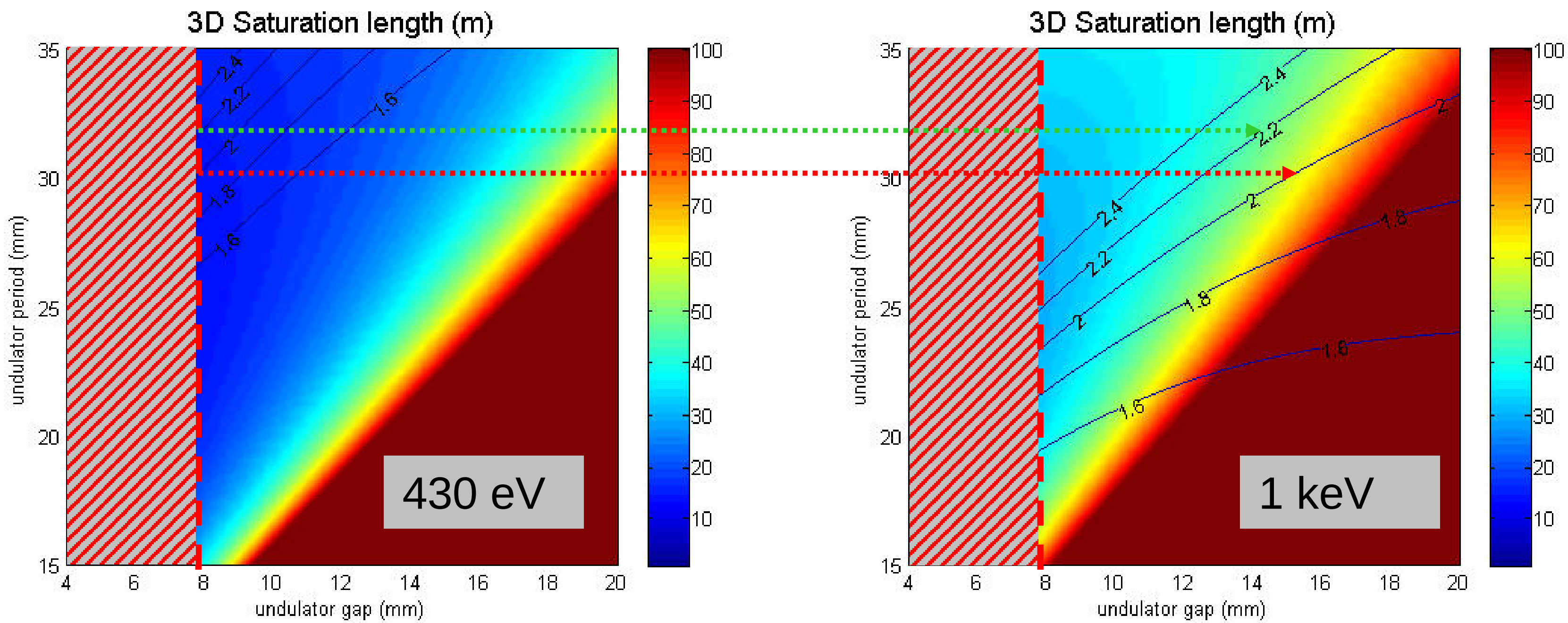


FEL working point

Working point defined by:

- minimum allowable undulator gap at 430 eV (8 mm)
- saturation length at 1 keV $\rightarrow$ requirements on K (K > 0.7) and beam quality

Using Xie parameterisation with I_{peak} = 1 kA, ε_n = 1µm, $\sigma_\varepsilon = 5{\cdot}10^{-4}$



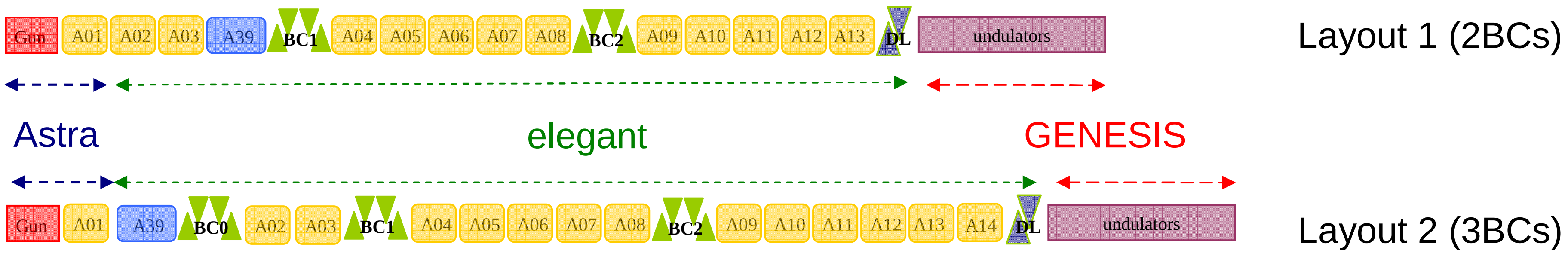
λ_u = 32 mm; g = 8 mm

K = 1.56; < β > = 5 m

λ_u = 32 mm; g = 14.4 mm

K = 0.67; < β > = 10 m

Numerical optimisation of a 2.2 GeV LINAC (I)



- Tracking studies to optimise the beam quality at the beginning of the undulators

  peak current, slice emittance, slice energy spread, etc…

- elegant simulations include

  CSR, longitudinal space charge, wake-fields in TESLA modules

- Parameters used in the optimisation

  Accelerating section and 3HC amplitude and phase,
  Bunch compressors strengths

- **Validation with full start-to-end simulation <u>Gun to FEL</u> (time dependent)**

Numerical optimisation of a 2.2 GeV LINAC (II)

Main issues and guidelines for the optimisation

- compression should not introduce space charge and CSR issues

  avoid strong compression at lower energy

- linear optics tailored to reduce CSR (e.g. minimum horizontal beta at 4th dipole)
- compression aided by linearisation of longitudinal phase space with a 3HC
- analytical formulae for 3HC setting, microbunching gain curves, …
- beam quality optimisation driven directly by the required FEL performance

We have devised a multi-parameters multi-objectives optimisation of the LINAC working point based on the Xie parameterisation (semi-analytical expressions) for the gain length and the FEL saturation power. We target

gain length, FEL saturation power as in a SASE FEL

and due to the additional complication with seeding

simultaneous optimisation of many slices to achieve a flat portion of the bunch (length ~ 100 fs) with constant slice parameters

Numerical Optimisation of a 2.2 GeV LINAC (III)

We have adopted a multi-objectives multi-parameters optimisation of the LINAC

based on a fast numerical computation of the Xie gain length vs LINAC parameters

Xie gain length $L_{3D} = L_{3D}(\varepsilon_x, \sigma_\varepsilon, \sigma_x, \ldots)$

Compute the "slice" properties ε_x ,σ_ε, σ_x, … from elegant

$$L_{3D} = L_{3D}(V_1, \ldots, V_n, V_{3HC}, \phi_1, \ldots, \phi_n, \phi_{3HC}, \theta_1, \theta_2, \ldots)$$

Objectives:

L_{3D}, P_{sat} **AND** length of the "good slice region" (compression strength, …)

Parameters:

amplitudes and phases of RF accelerating sections, compressors, …

Parallel Search Algorithms (Genetic Algorithm SPEA)

Multi-objective multi-parameter optimisation

18000 runs with 100K particle each

2 objectives: minimise Xie Length and maximise and P_{sat}

4 parameters: phase of ACC02; ACC4-7, BC1, BC2

<u>*Manual optimisation (red dot)*</u>

xie length 1.24 (m)

avg sat power 2030 (MW)

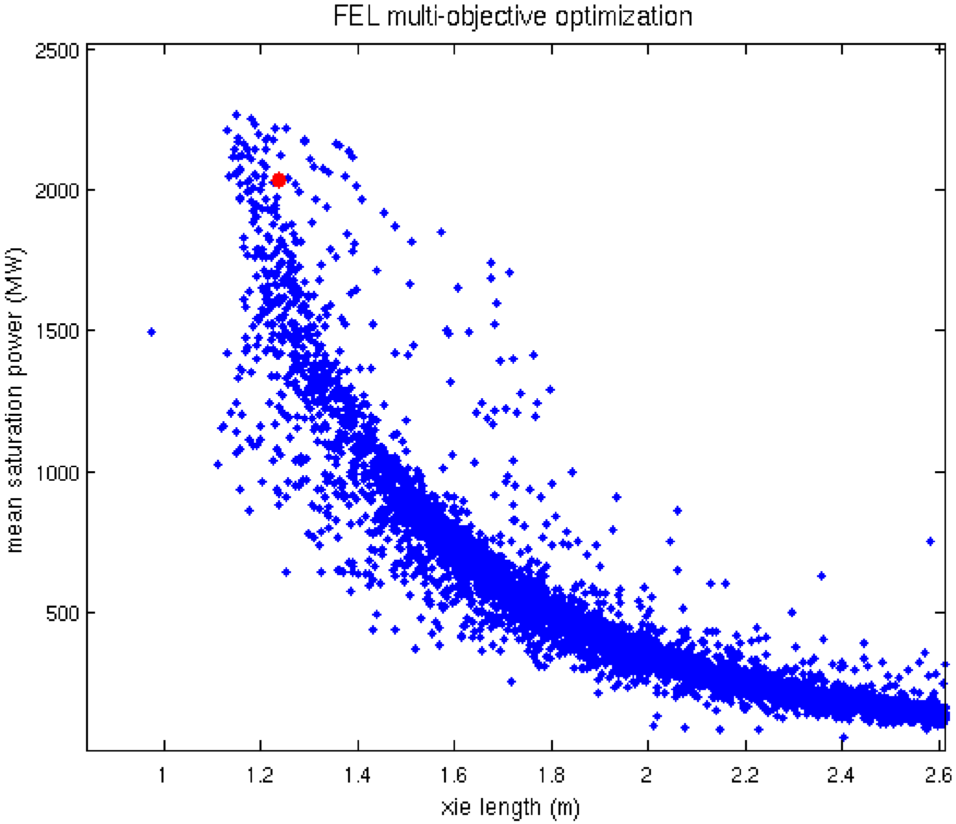
$(\theta_2, \theta_3, \varphi_2, \varphi_4)$ = (17.5, 6.1, 7.75, 25)

<u>*Multi-objective optimisation*</u>

xie length 1.15 (m) (–8%)

avg sat power 2220 (MW) (+11%)

$(\theta_2, \theta_3, \varphi_2, \varphi_4)$ = (17.54, 4.92, 8.96, 29.91)



The Xie length is averaged over the slices covering a portion of 100 fs of the bunch

Optimised beam from the L-band injector

L-band NC gun optimisation ongoing

ASTRA to deal with space charge issues

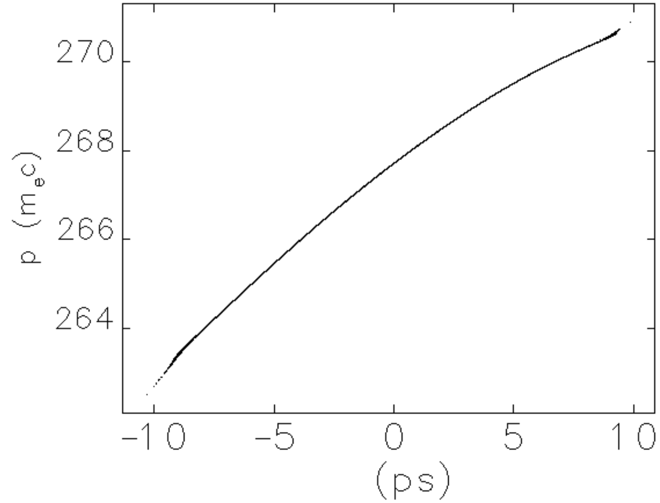
200 pC – 20 ps FW – 130 MeV

Normalised slice emittance below 4·10^{-7} m

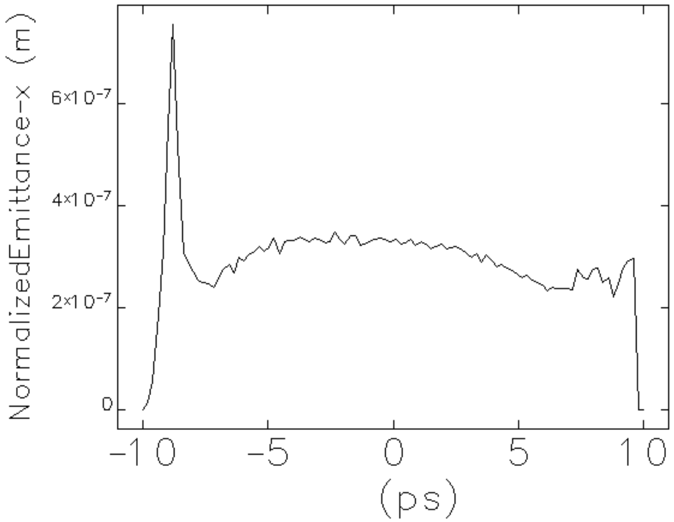
Slice relative energy spread below 2 ·10^{-5}

I peak ~ 15 A

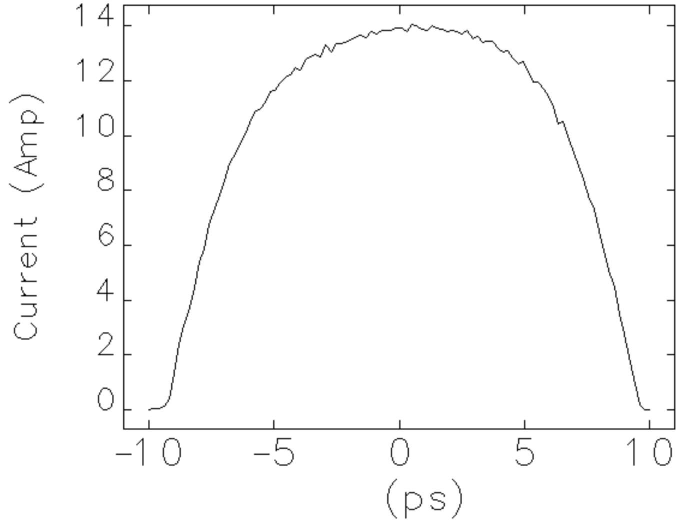
Longitudinal phase space



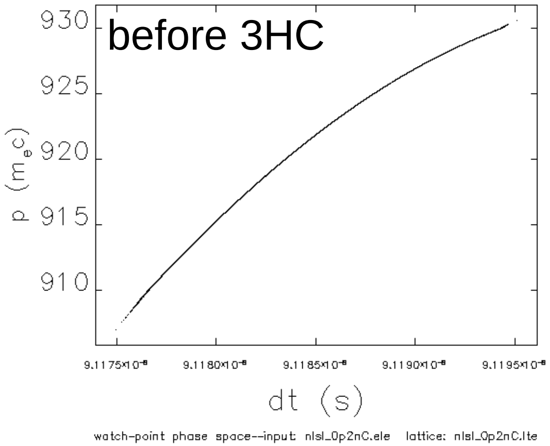
Slice normalised emittance

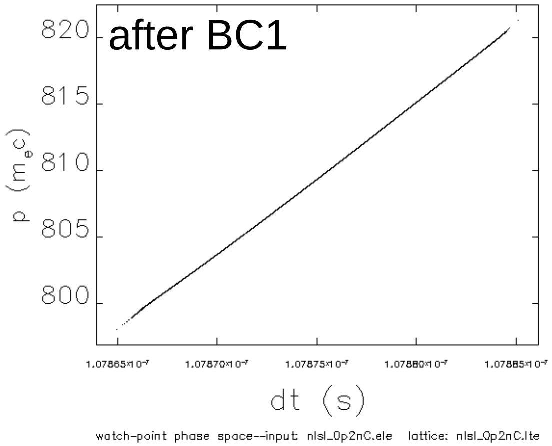


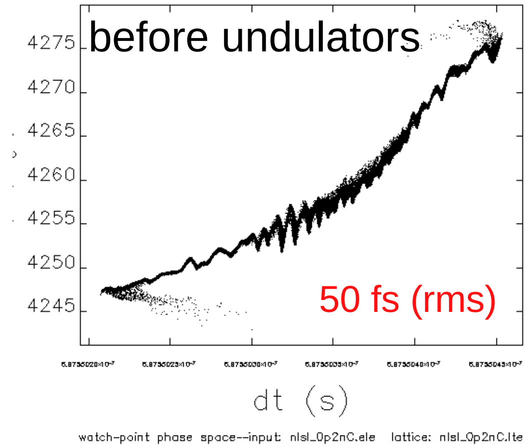
Longitudinal current distribution

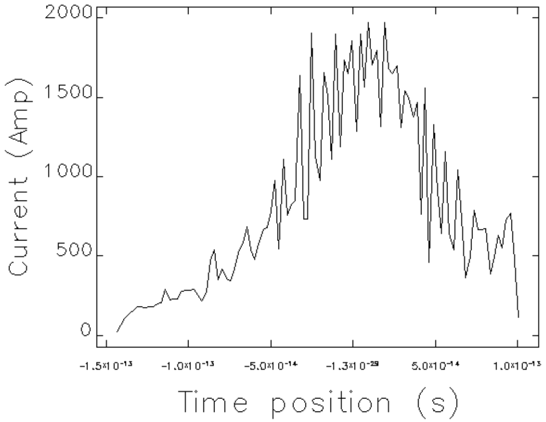


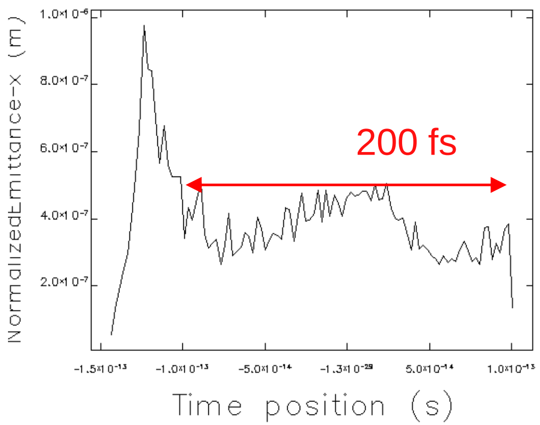
Beam properties along the LINAC: layout 1 (2BCs)

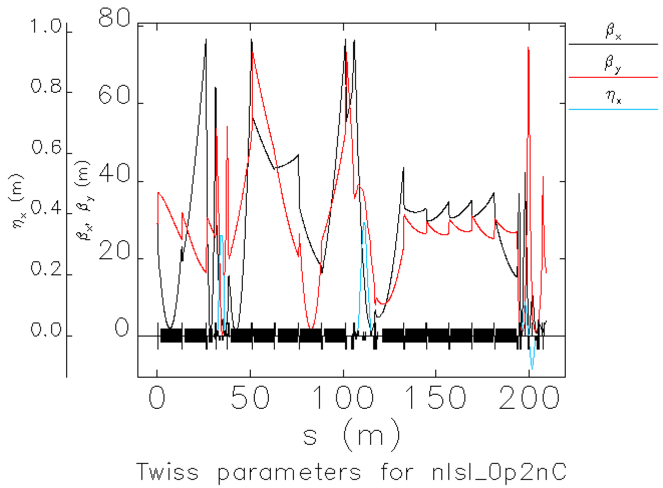






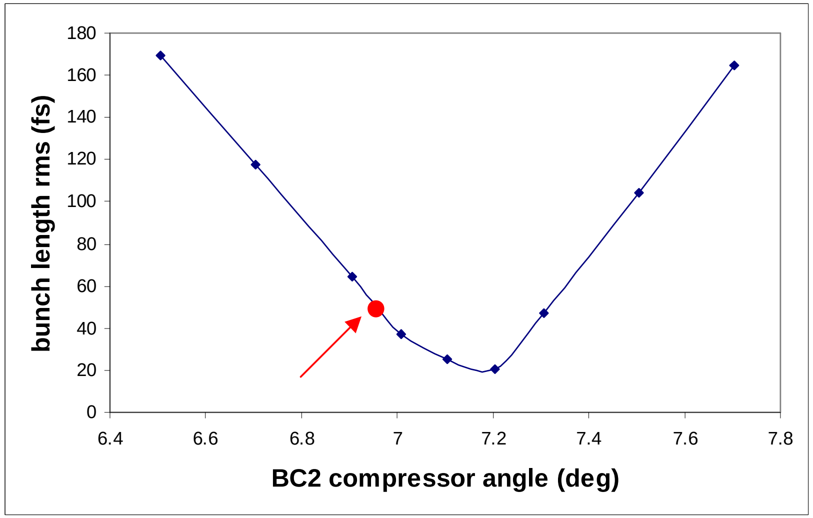


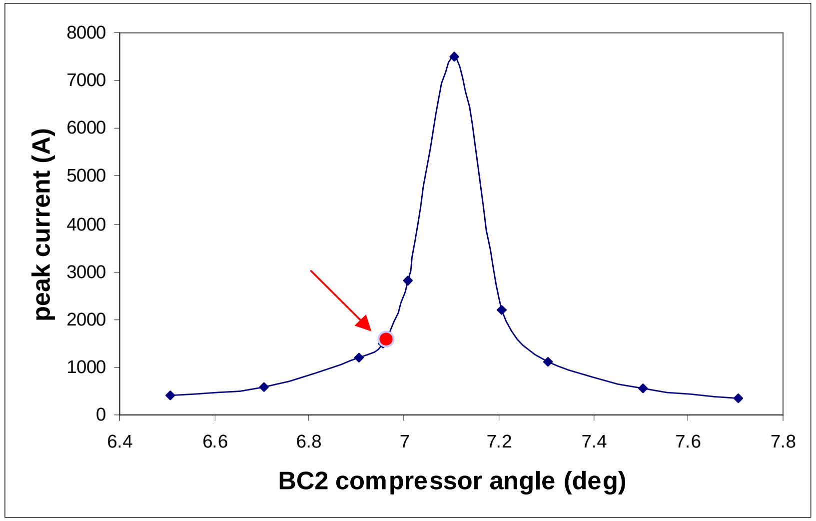


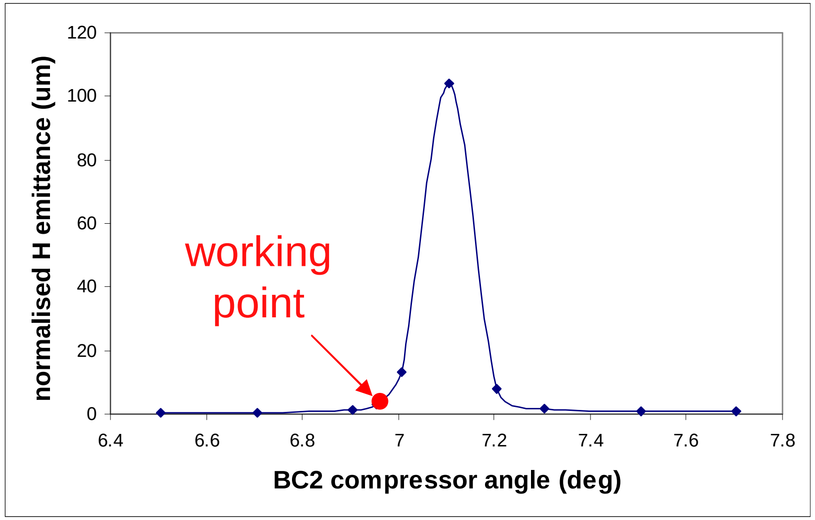


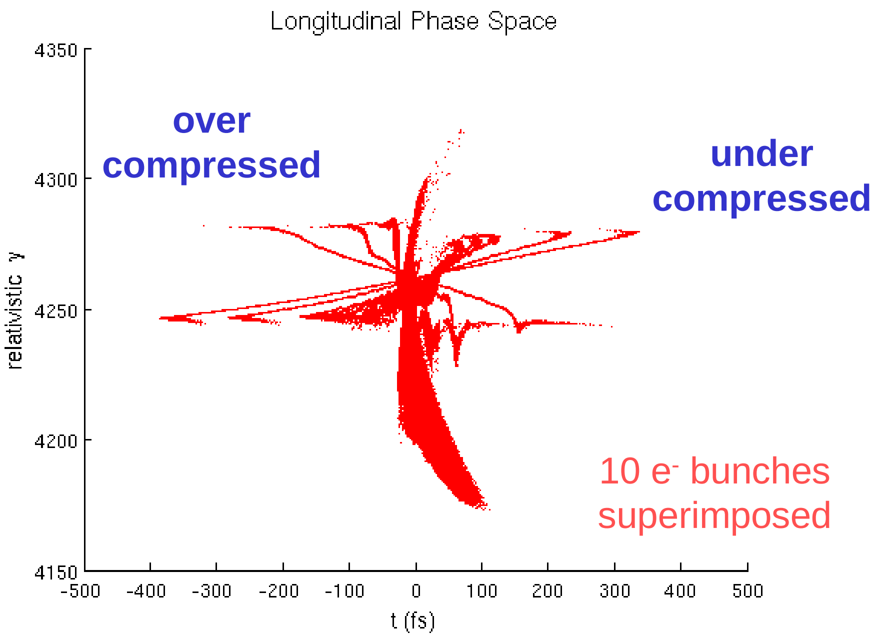
BC2 6.95 deg; best slices I_{peak} ~ 1.7 kA, ε_n ~ 0.4 μm, σ_ε ~ 10^{-4}; 50 fs (rms)

CSR issues and compression optimisation (BC2)



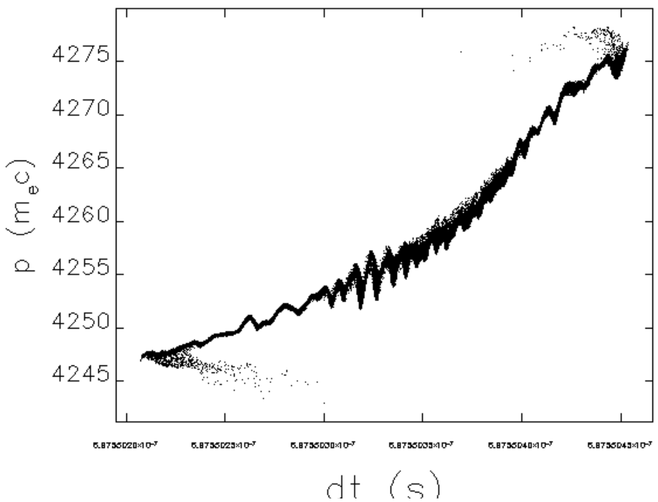


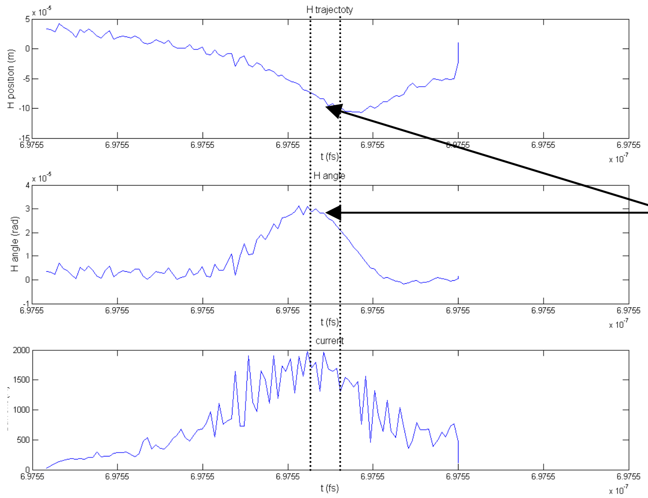




FEL Time dependent S2E simulations

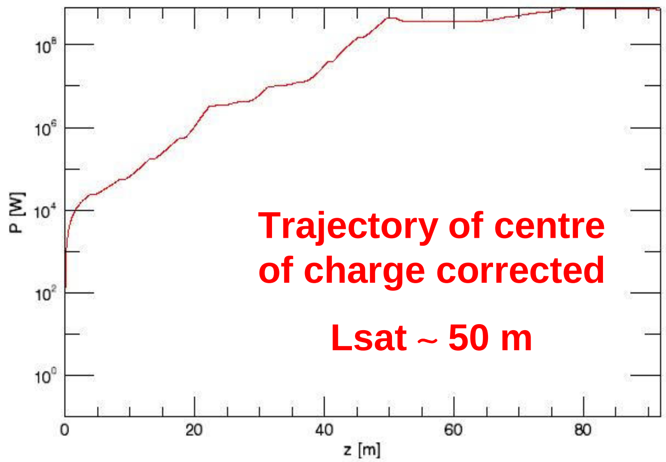
λ_u = 31.9 mm; g = 14.4 mm; K = 0.67

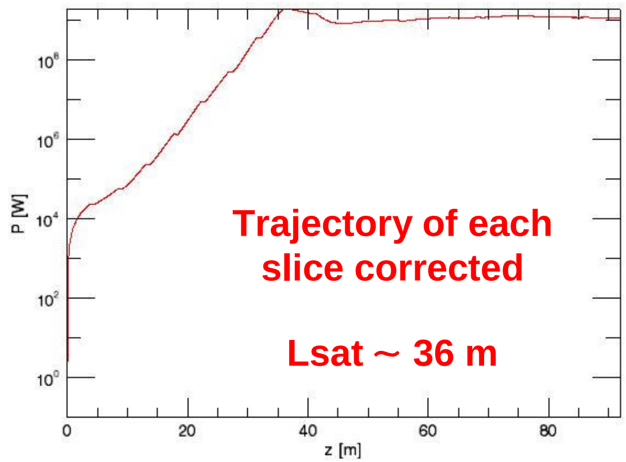




These offsets in position and angle kill the gain

70 μm and 30 μrad





Issues and alternative layouts

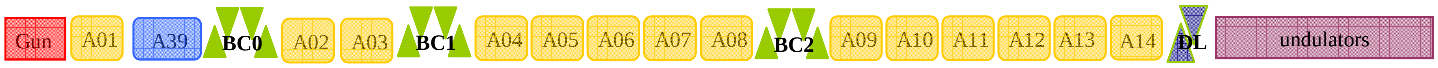
The main issue with the 2BC layout is the need to reduce 3HC gradient (~40 MV/m):

Several attempts were made

generating a shorter (15 ps FW) and more linear bunch from the gun

and/or add on more 3HC module (FLASH Type with 4 cavities per modules)

or add on more (weak) bunch compressor

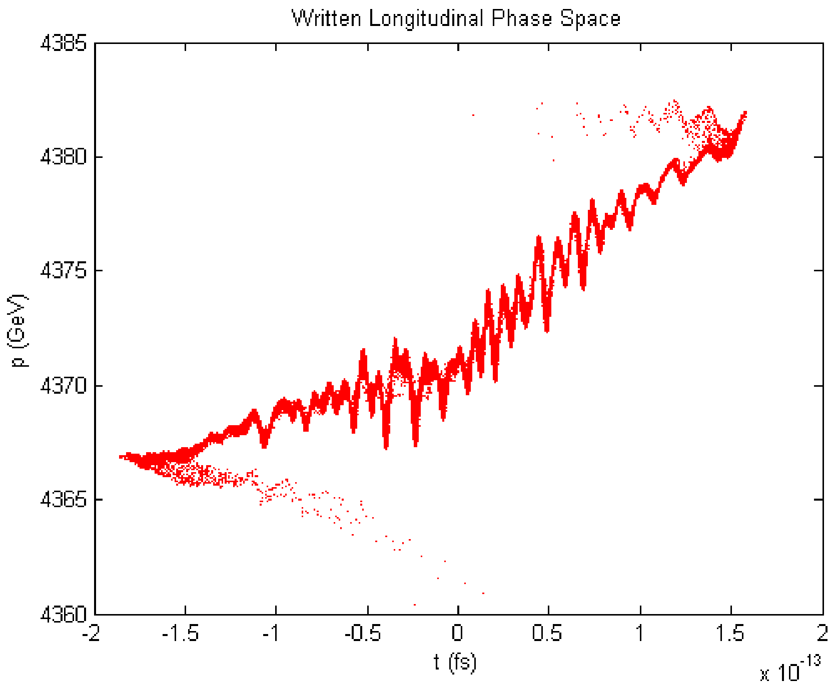


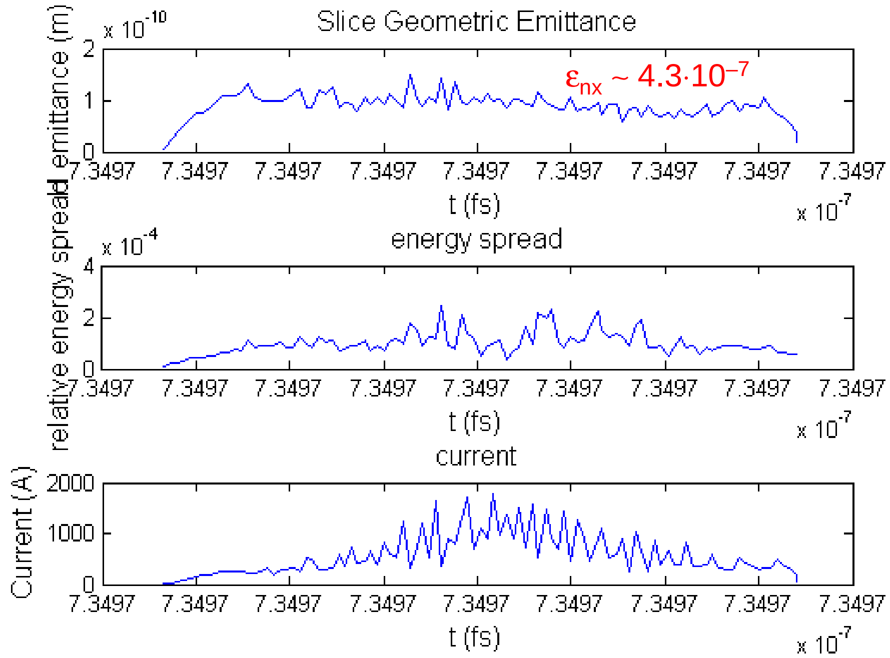
or other locations of BCs …

Beam properties along the LINAC: layout 2 (3BCs)

135 MeV	110 MeV	440 MeV	1.2 GeV
18 ps	10 ps	2 ps	300 fs

3HC at 3.9 GHz can work at 15 MV/m; No need of a second 3HC before second BC;



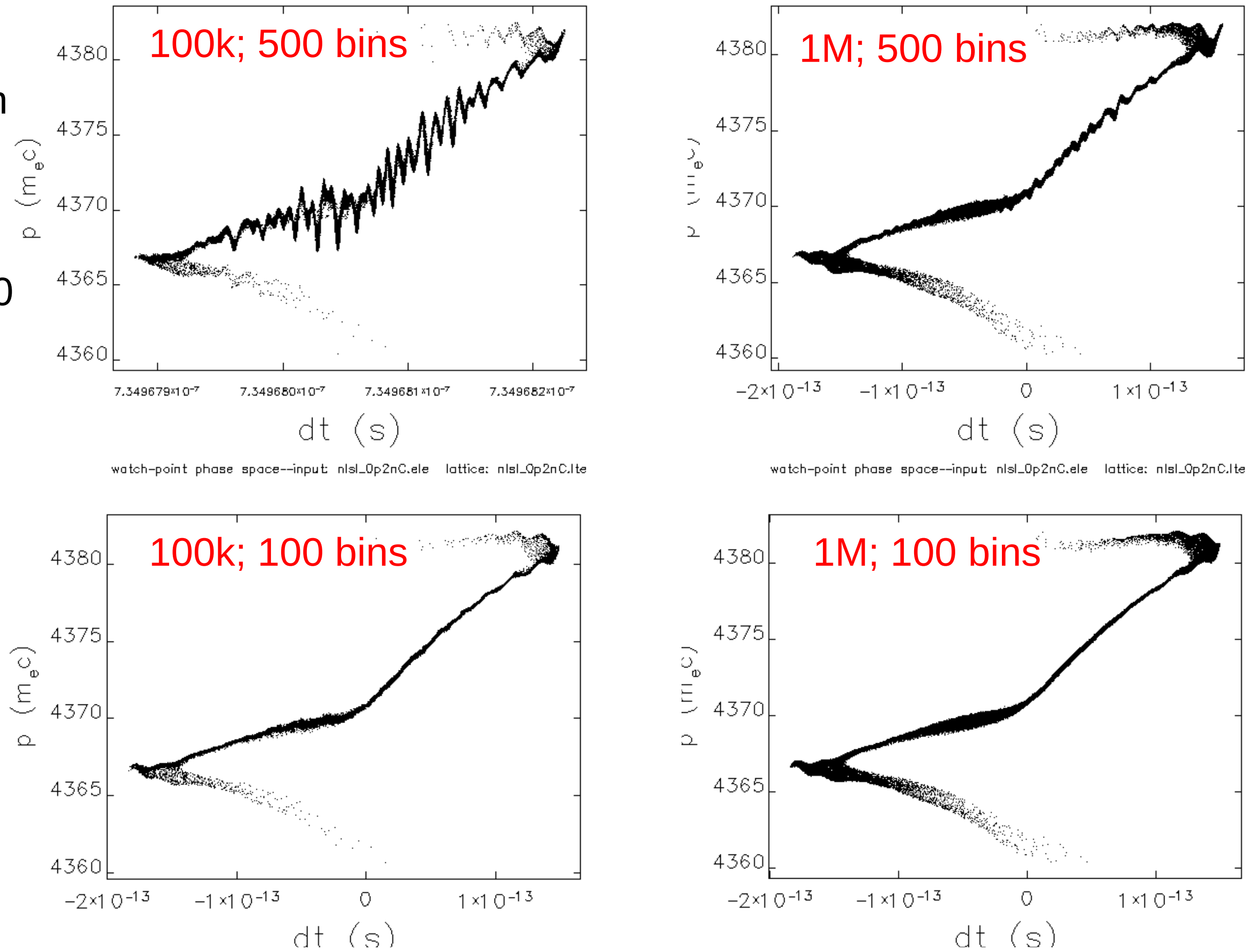


Numerical issues with CSR

Significant Modulation with period

~ 7 fs – 2 um

Compression factor 70
→ ~ 500 fs
at the cathode



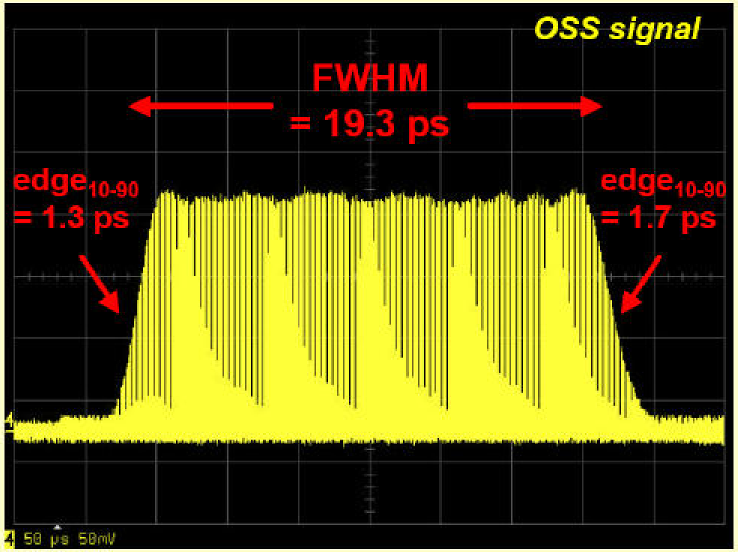
200 pC optimised case; 100k particles; NBINS = 500; jagged longitudinal phase space

Still OK for SASE – but too spiky(?) for HGHG

Numerical issues with CSR

Sources of density fluctuations – shot noise; external causes (e.g. laser flat top,…)

Shape of the UV laser pulse (24. Oct. 08)



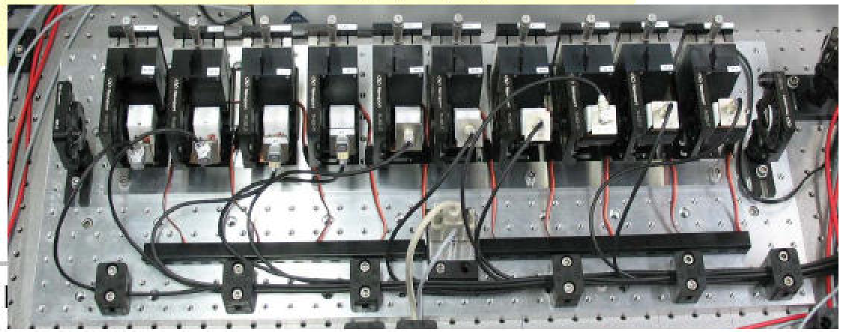
(10-20% calibration uncertainty ?)

Notes:

- This is measured without Lyot filter.
- When inserting the Lyot filter in the regen, the pulse will be “smeared out”, i. e. a slightly longer pulse with longer edges will be produced

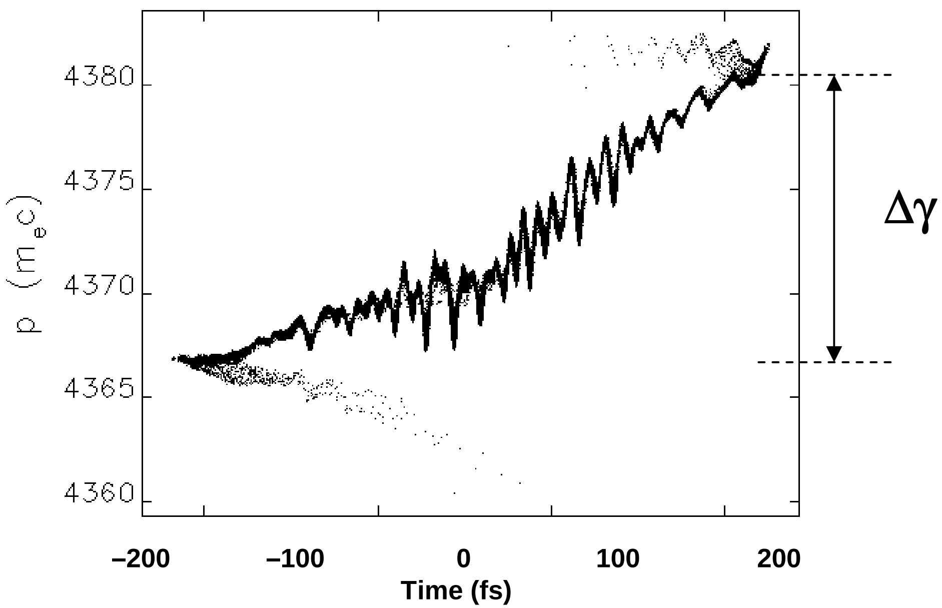
Ingo Will: flat-top laser pulses at PITZ

10 individual crystals determine the shape at different longitudinal positions within a laser pulse



Energy chirp issues (I)

Energy chirp should be smaller than the SASE intrinsic BW ($\sim\rho = 10^{-3}$)



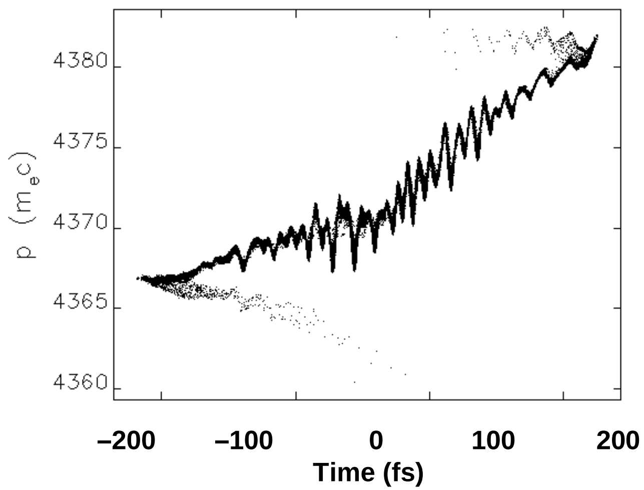
$\Delta\gamma / \gamma = 3.2\ 10^{-3}$

~ 3 times larger than the SASE BW

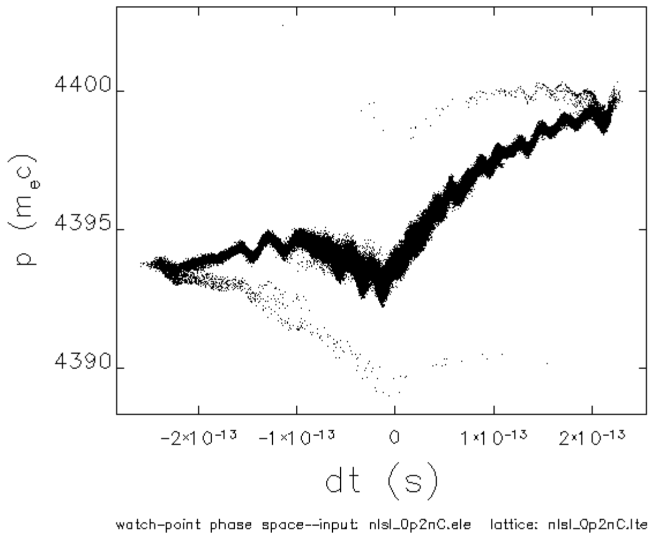
Comparing to numerical simulations at LCLS-FERMI wakefields were crucial in flattening the residual chirp. Larger energy helps (large γ and longer linacs)

Energy chirp issues (II)

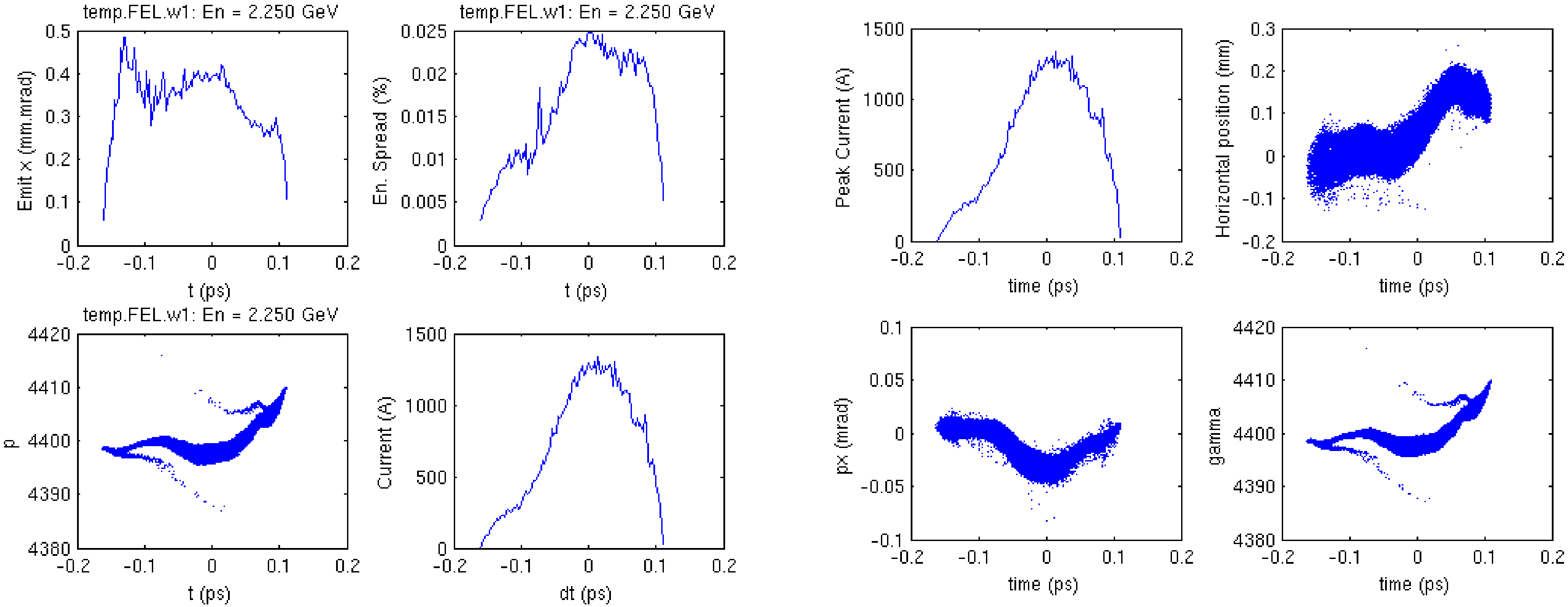
- use wakefields
  - in L–band structures wakefields are weaker than in S-band
  - 200 pC too small
- use the main RF to reduce chirp accelerating “beyond crest”
  - bunch too short after 3BC (RF slope sampled is too small)
  - L-band has a smoother curvature than S-band
- use less chirp from the beginning



$\Delta\gamma / \gamma = 1.6\ 10^{-3}$
reduced but larger
compression !



C-type chicanes

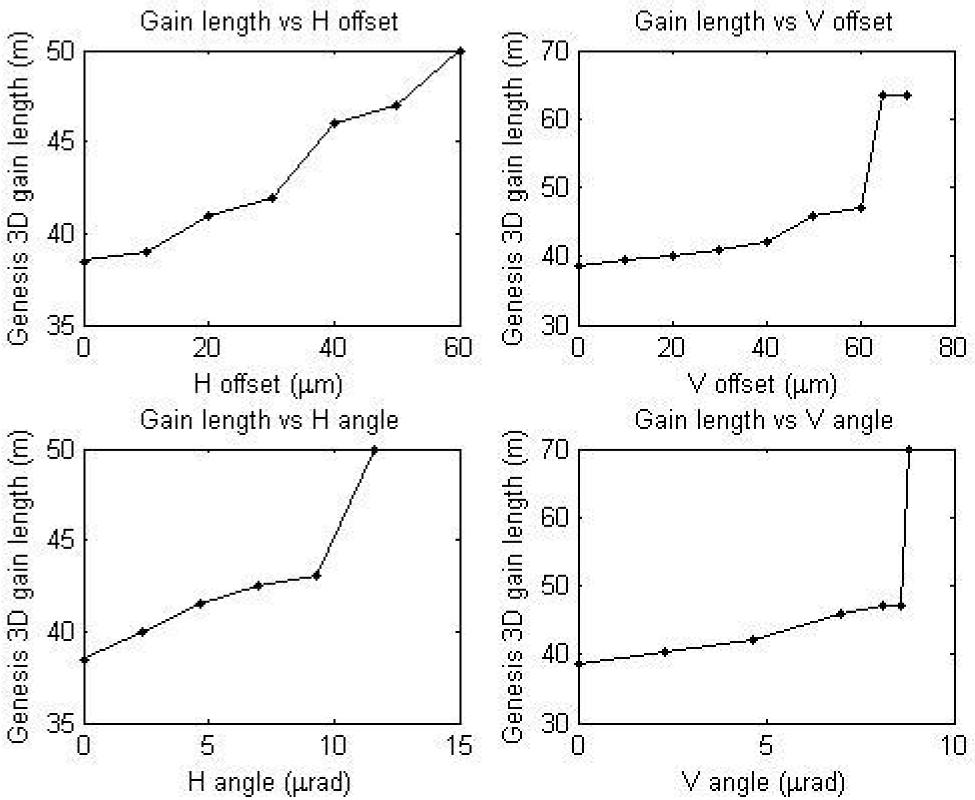


3D gain length with beam offset and angle

Using genesis SS simulations adding H offset, V offset, H angle, V angle

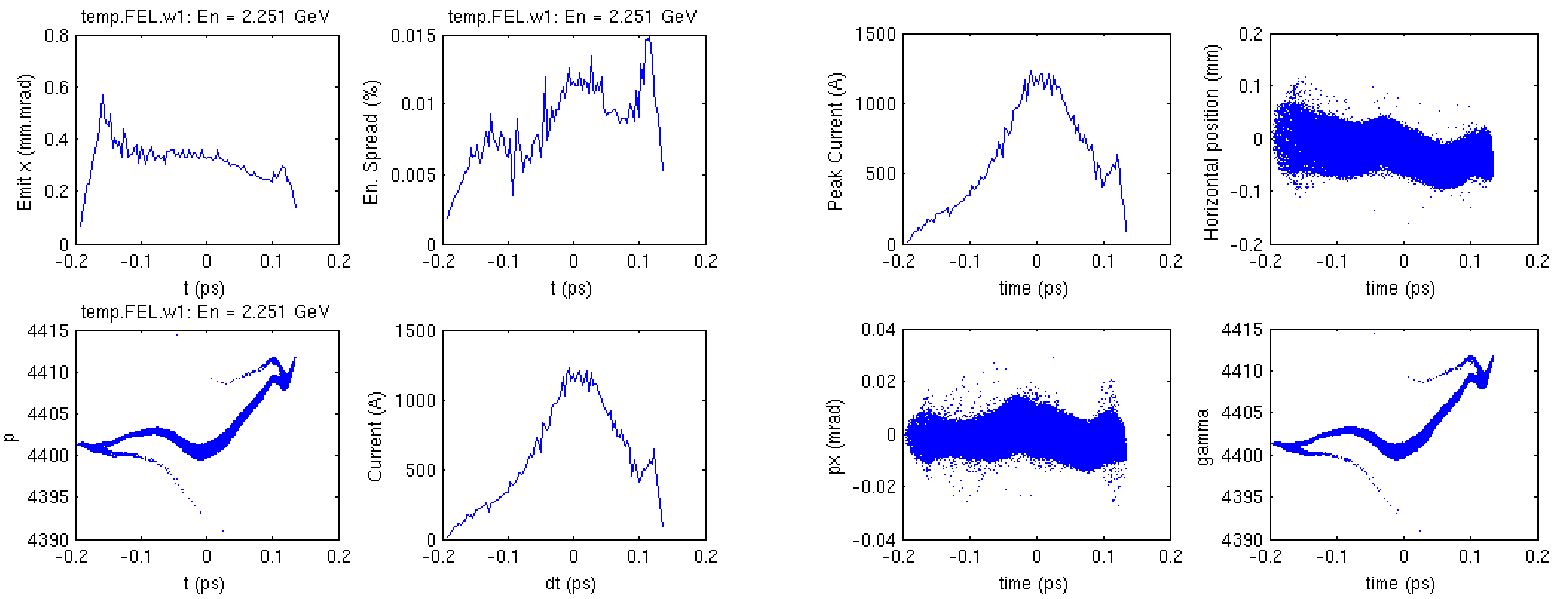
Trying to parameterise as per Xie formalism

(normalis. emitt. ε_x = 0.4 um, relative energy spread 2e-4, I peak = 2 kA)

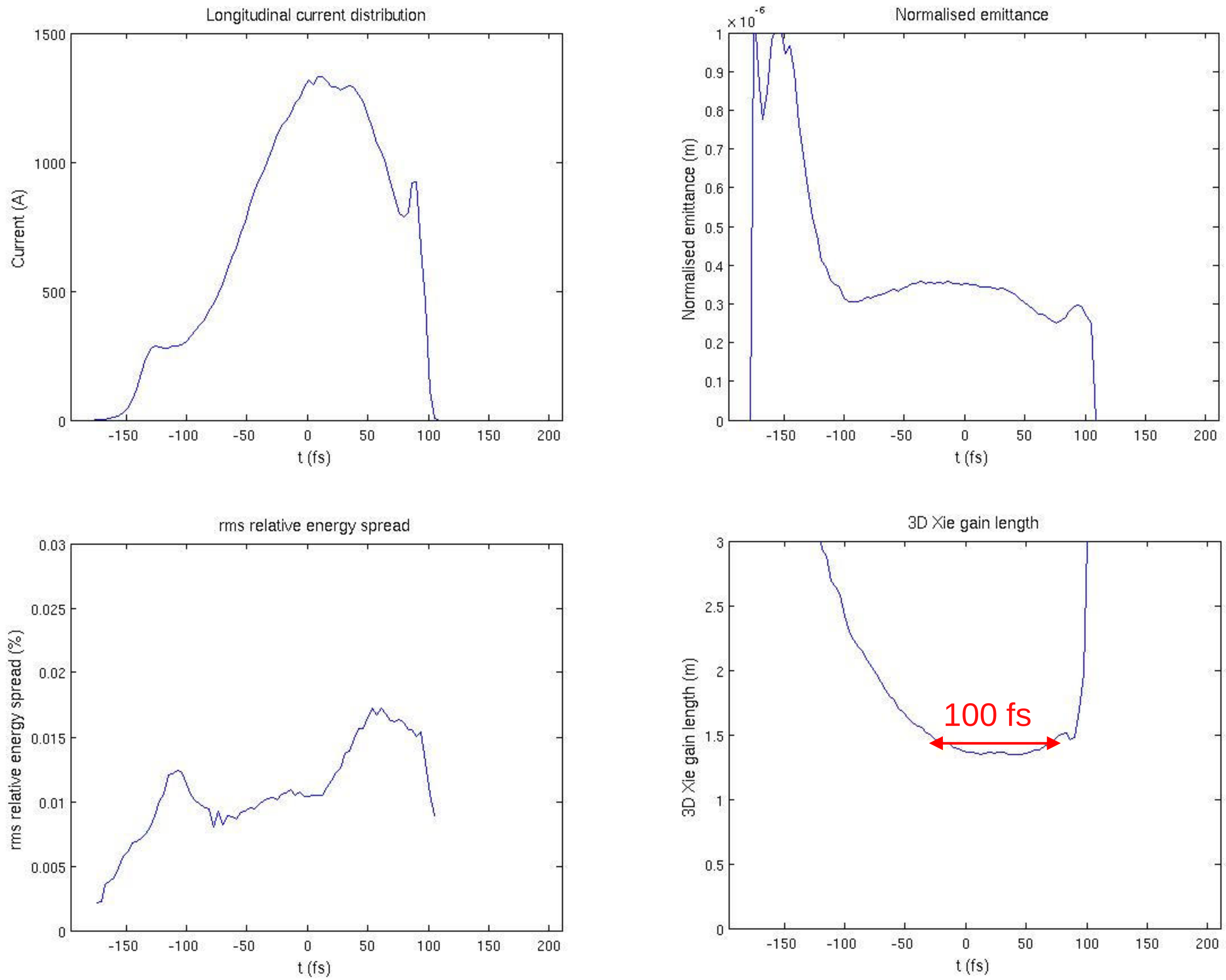


Angle dependence is very critical ! (tbc)

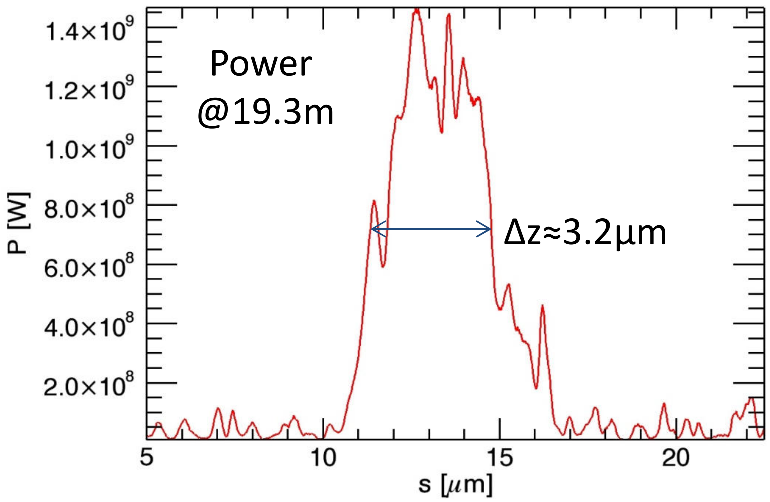
S-type chicanes

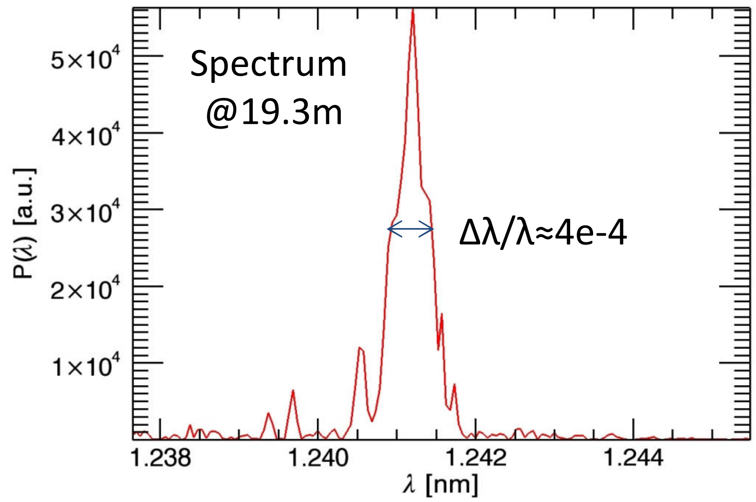


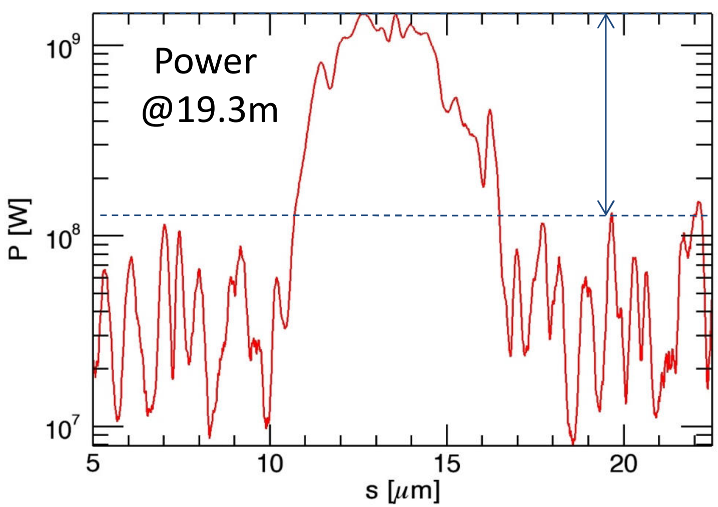
200 pC best optimisation



Cascade Harmonic Scheme output







Time-bandwidth product ≈ 1
Contrast ratio ≈ 15

Jitter studies

The FEL performance can be severely spoiled by jitter in the electron beam characteristics

To understand this issue we have started a numerical investigation of the sensitivity of the beam quality to various jitter sources:

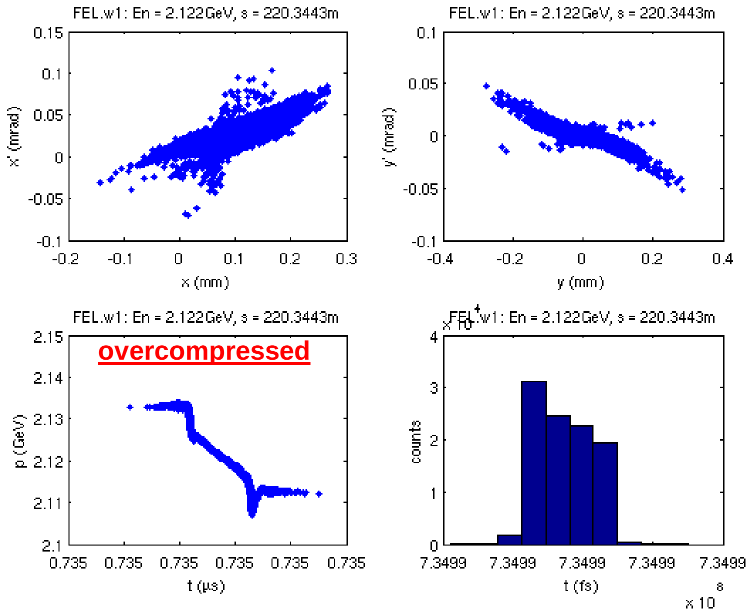
- phase and amplitude of RF sections
- bunch compressor power supplies

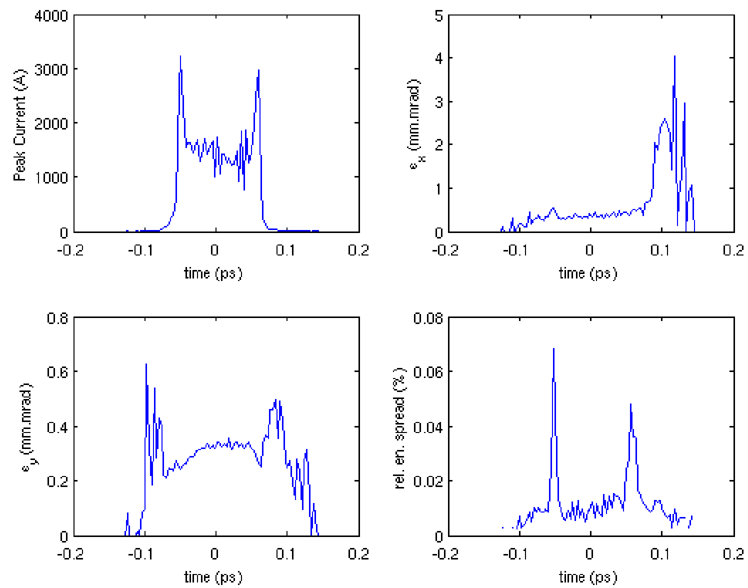
Adding the jitter sources one-by-one and all together as random noise

Jitter in the GUN was also included

- gun phase and voltage
- solenoid field
- charge
- laser spot position jitter

FEL time dependent simulations with 3BC layout (multi-parameter optimisation)



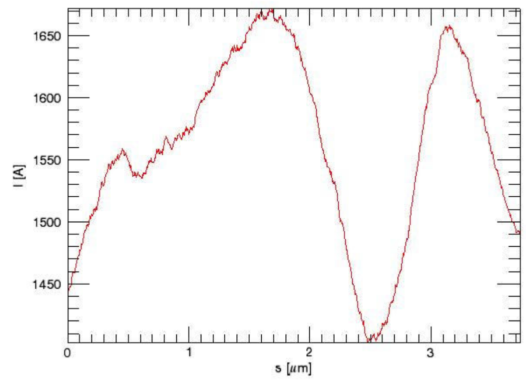


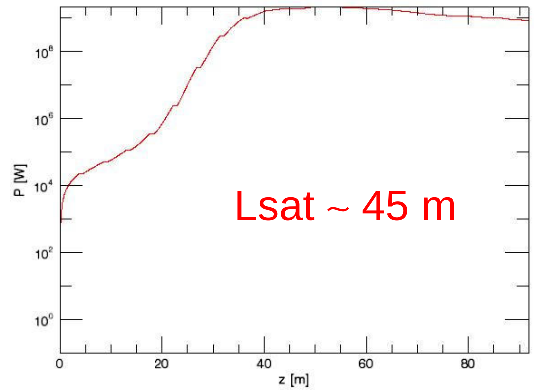
Best slice: $\varepsilon_x = 4{\cdot}10^{-7}$ m ;

$\sigma_\gamma = 8{\cdot}10^{-5}$;

$I_{peak} = 1.6$ kA;

along 100 fs or more **with a flat plateau** (typical for overcompressed bunches)





200 pC jitter

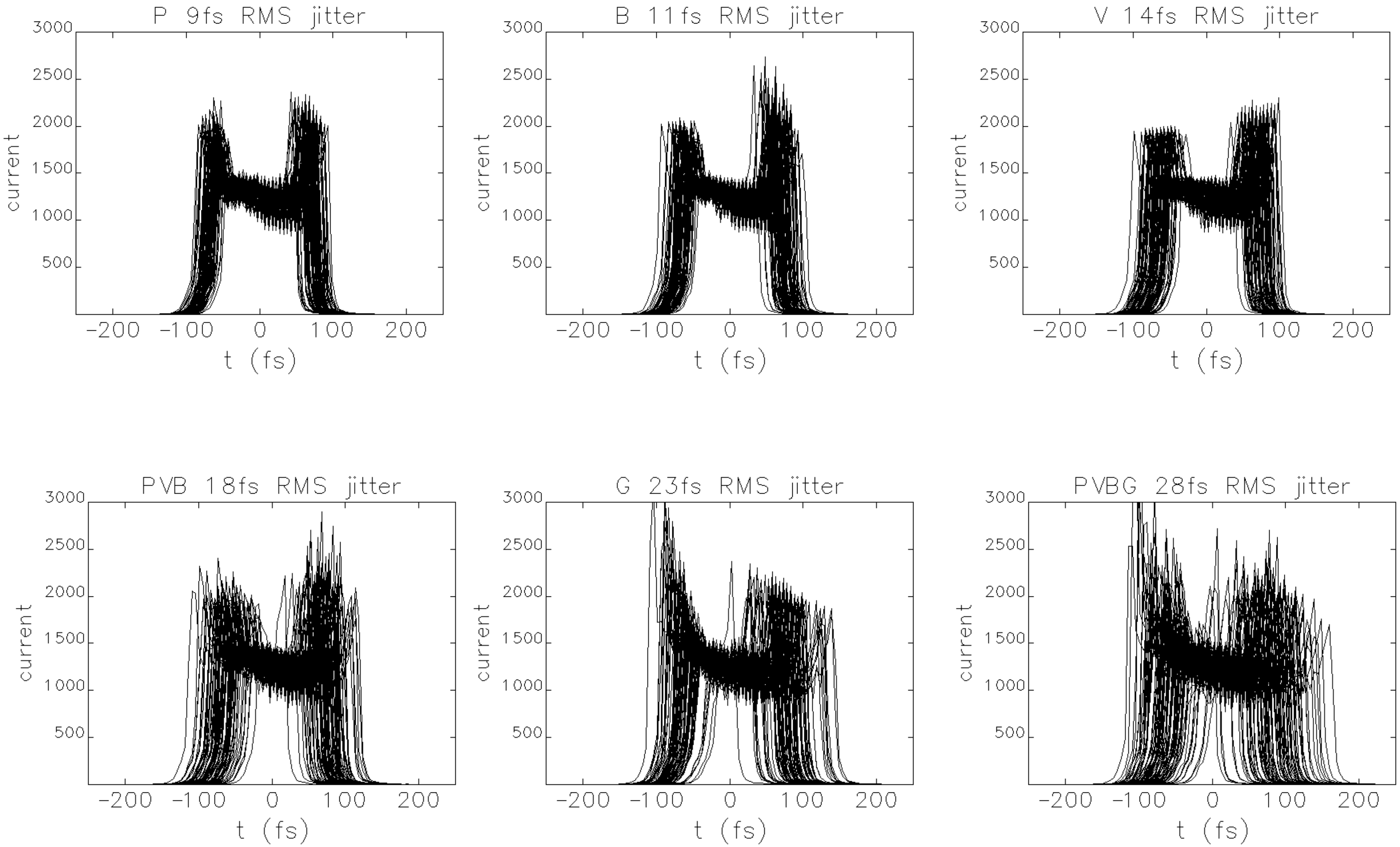
Gun Jitter Parameters (standard deviations)

Solenoid Field	0.02e-3	T
Gun Phase	0.15	degrees
Gun Voltage	0.05	MV/m
Charge	1%	
X Offset	0.025	mm

Arrival Time Jitter at end of LINAC (standard deviation, fs)

Phase (P)	0.01 degrees	9
Bunch Compressor (B)	5e-5 fractional	11
Voltage (V)	1-e4 fractional	14
Gun (G)		23
P + V + B		18
P + V + B + G		28

200pC Beam profiles with jitter

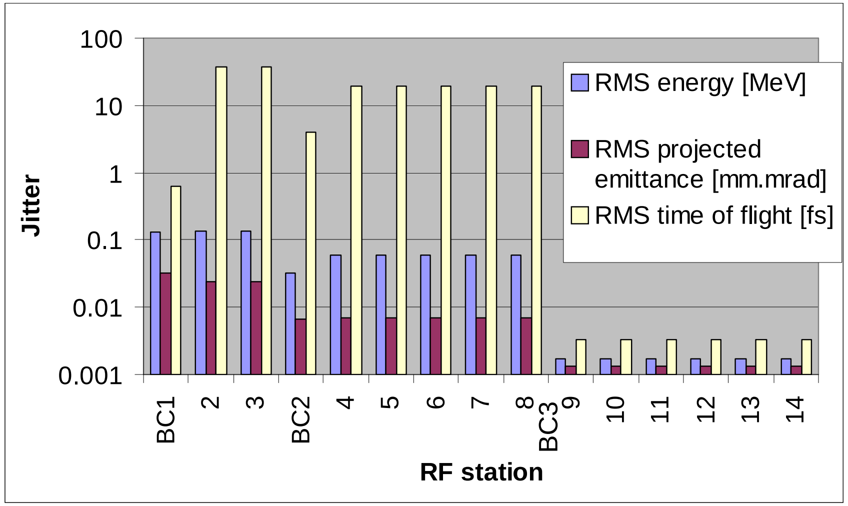


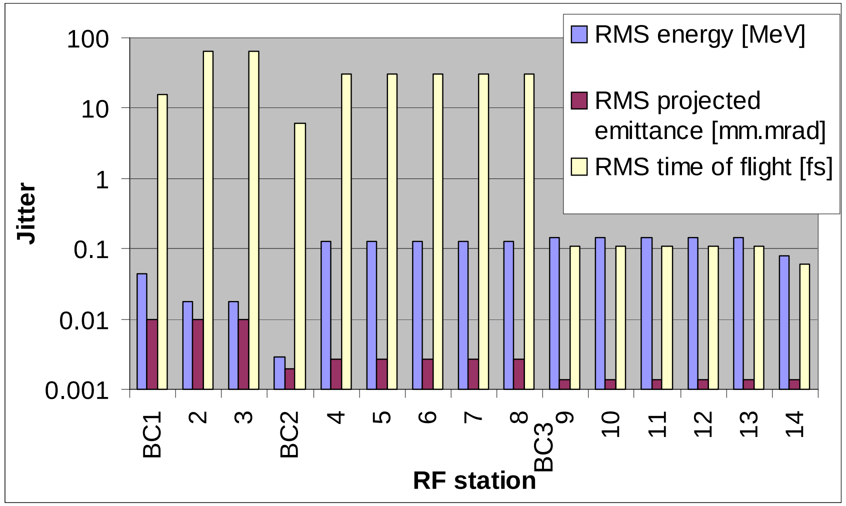
Beam jitter causes from the LINAC RF

Applying jitter errors in the amplitude and phase of the RF station one by one we can determine the impact of each accelerating section on the beam parameters

The plots refer to the extreme case of 0.1 degrees phase jitter and 0.1% voltage jitter to

- **RF stations near the start of the linac contribute a large amount to jitter**
- **Concentrate on minimising jitter in RF stations between first two bunch compressors but cannot neglect contribution from structures between bunch compressors 2 and 3**
- **Cavities after 3BC play little role**





Conclusions and future work (I)

We have produced a "promising" layout of a single-pass LINAC which can deliver an electron beam with the required properties with modest improvements on the present technology – requirement on 3HC and RF jitter to be further analysed

SASE FEL performance achieved exceeds the 10^{11} ppp @ 1 keV

Alternative FEL operating mode under consideration (Single Spike; different charge)

Wakefield effects and jitter issues under consideration along with a thorough tolerance analysis;

Finalise layout choice: continue the evaluation of the 3BC vs 2BC layouts collaboration with LBNL (revisiting our 1BC design)

Acknowledgments:

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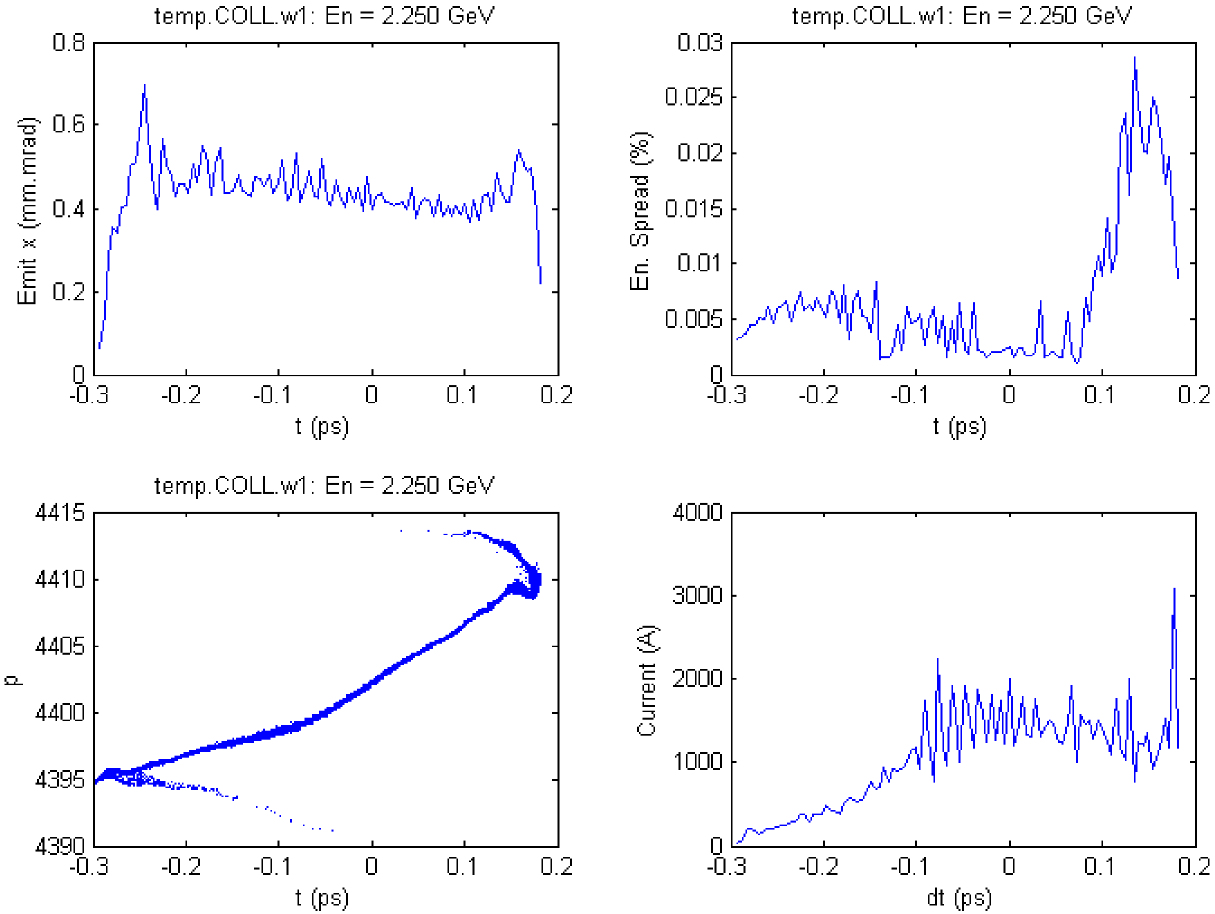
D. Angal-Kalinin, F. Jackson, B. Muratori, P. Williams (ASTeC)

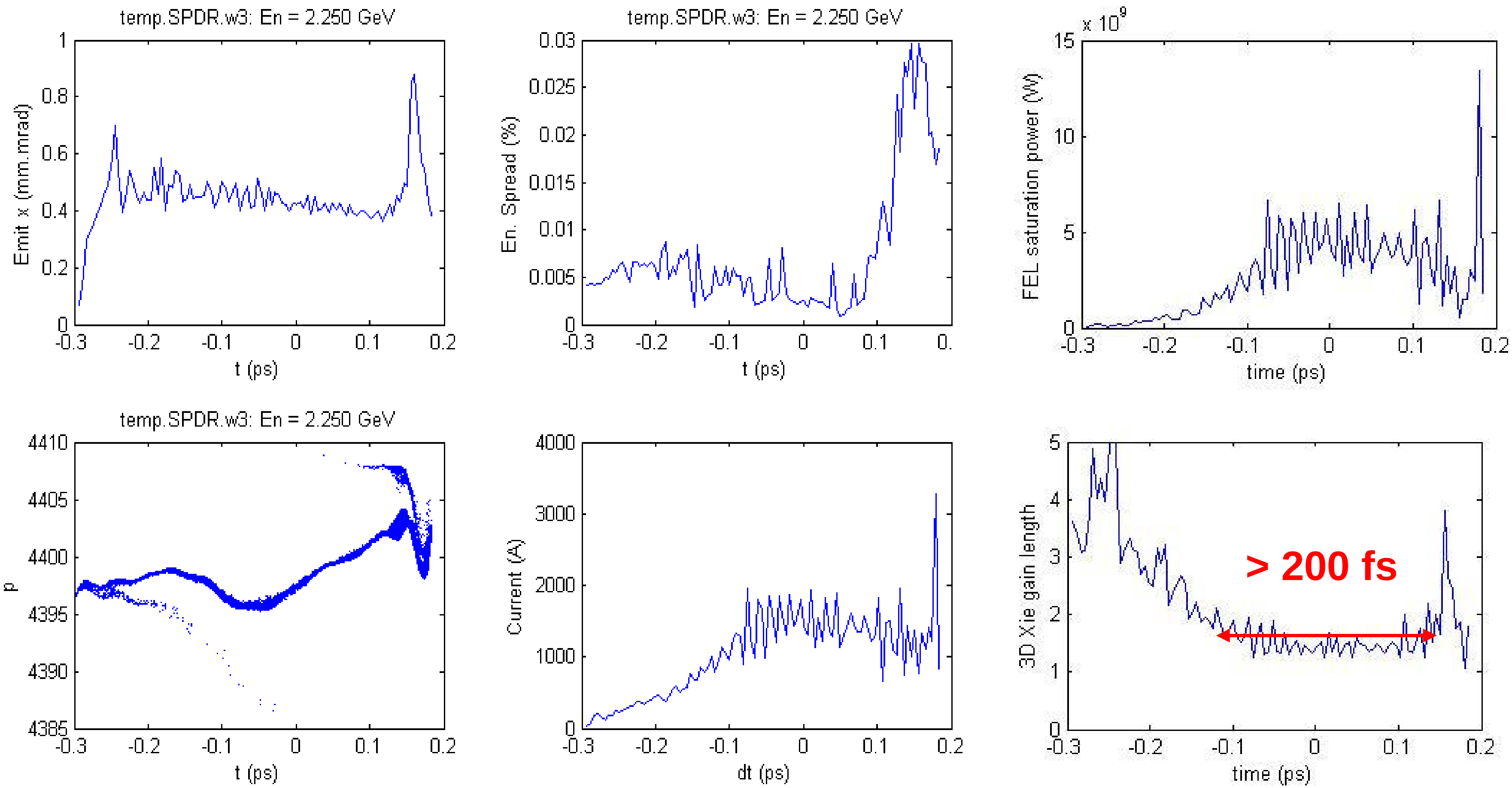
and the NLS Physics and Parameters Working Group

Optimisation for the operation at 500 pC

We consider also a longer electron pulses with constant slice parameters with at least 200 fs flat top (in view of jitter results)

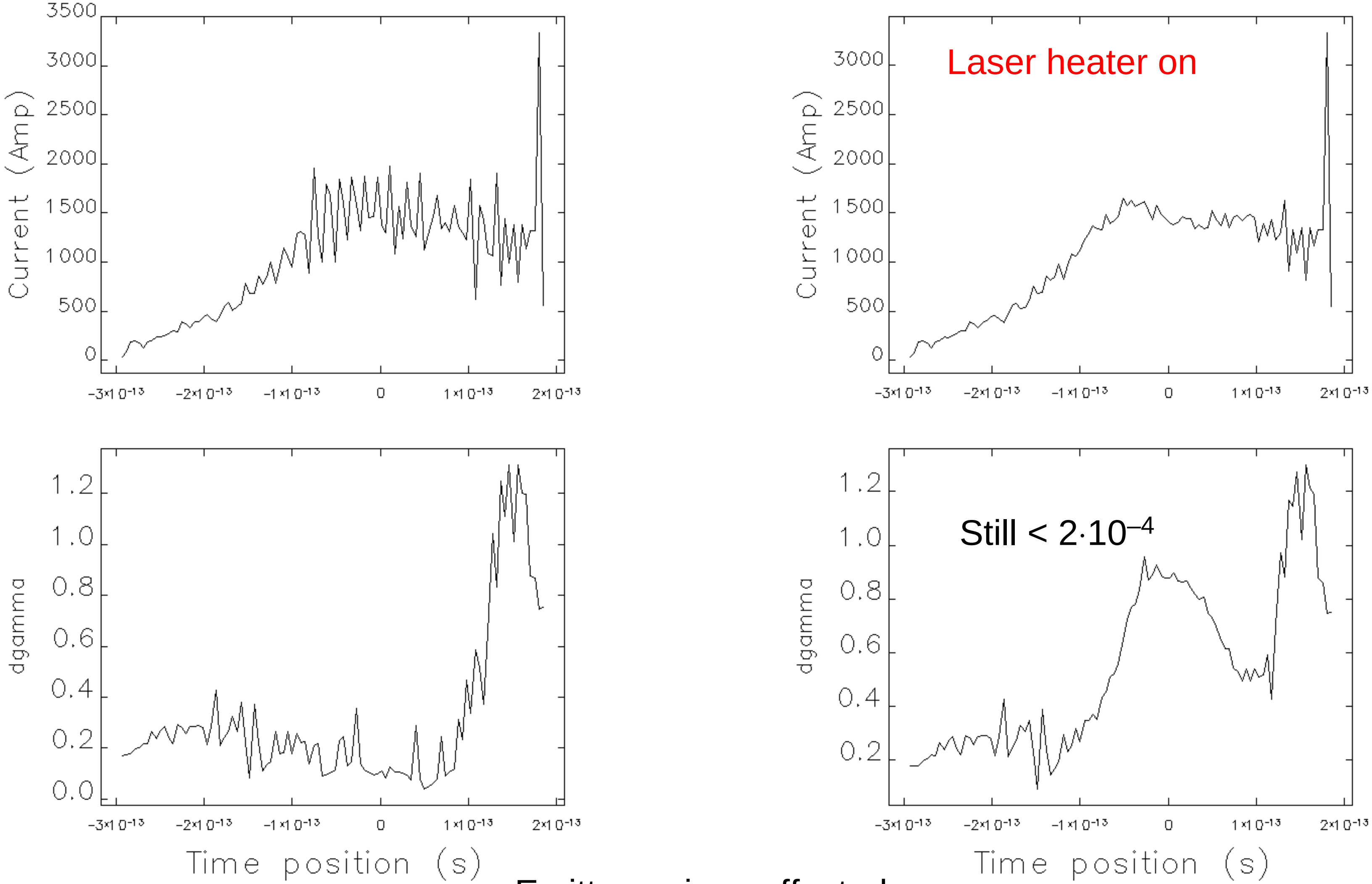


Exit of spreader section (500 pC)



Effect of the laser heater (500 pC)

The jagged longitudinal current profile is smoothed by the laser heater



Emittance is unaffected

500 pC jitter

Gun Jitter Parameters (standard deviations)

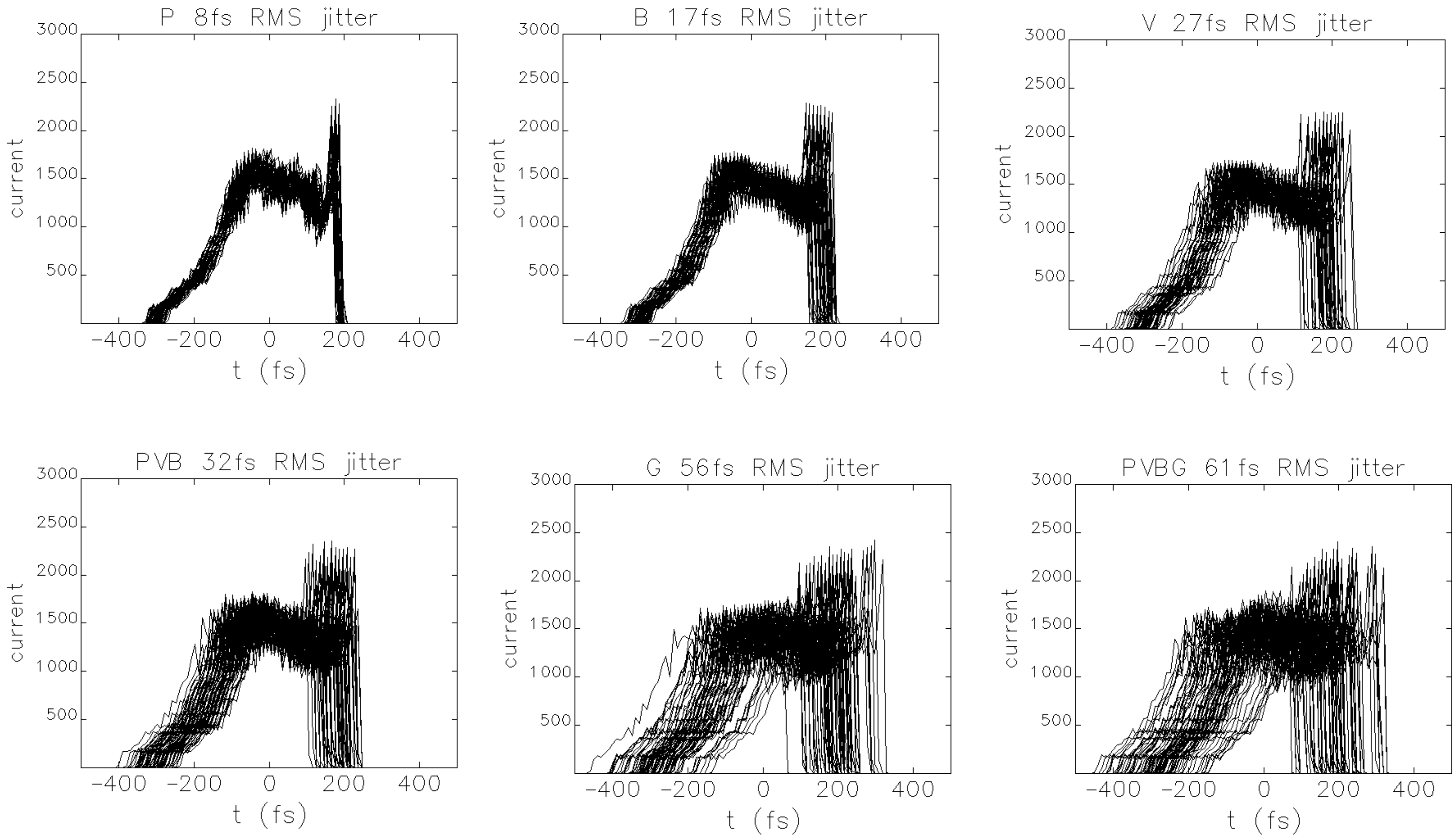
Solenoid Field	0.02e-3	T
Gun Phase	0.075	degrees
Gun Voltage	0.025	MV/m
Charge	1%	
X Offset	0.025	mm

Arrival Time Jitter (standard deviation, fs)

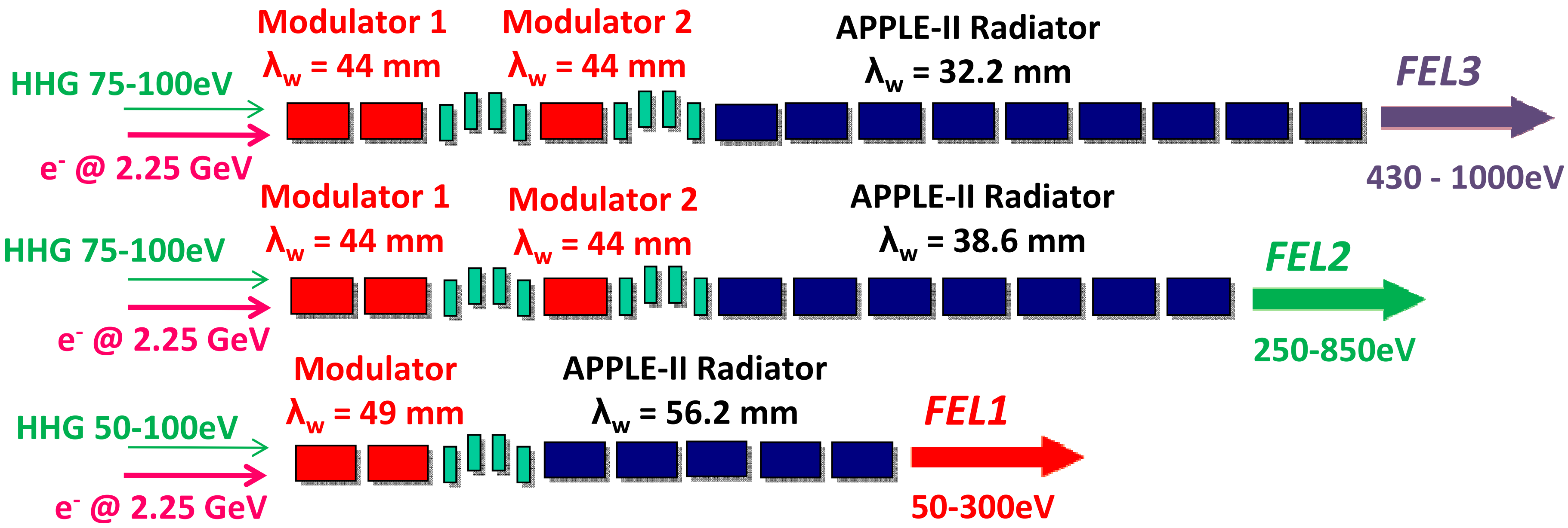
Phase (P)	0.01 degrees	8
Bunch Compressor (B)	5e-5 fractional	17
Voltage (V)	1-e4 fractional	27
Gun (G)		56
P + V + B		32
P + V + B + G		61

Requirements on the gun is even more stringent than in the 200 pc case

500pC Beam profiles with jitter



FEL Scheme (N. Thompson)



- common electron energy for all 3 FELs, allows simultaneous operation
- seeded operation for longitudinally coherent output
- HHG seeding with realistic laser parameters, up to 100 eV (100kW at 100 eV is realistic) (100 kW at 200 eV seeding level proved insufficient)
- harmonic cascade FEL scheme to reach up to 1 keV in the fundamental