Optimisation of a single-pass superconducting linac as a FEL driver for the NLS project

R. Bartolini, Diamond and John Adams Institute
for the NLS Physics and Parameters WG

Outline

- Introduction to the NLS project
- Linac layout; targets and results of the beam dynamics optimisation
- Jitter studies
- Optimisation for single spike operation at low charge
- Conclusions and future work

History of New Light Source Project

April 2008: official launch

Jointly supported by STFC and diamond (and involving various universities)

Phase 1:

consultation exercise with the UK user's community to define science drivers for a new light source and source requirements

Phase 2:

define the technical solutions and produce a conceptual design

September 2008: Science case and source requirements published

November 2008: STFC Science Board approved the science case and gave the go ahead to proceed with Phase II

July 2009: outline design report published

December 2009: submit the conceptual design report

NLS Outline Design Report (July 2009)

http://www.newlightsource.org/

The science case requires a light source with

- photon energies from THz to X-rays
- high brightness
- high repetition rate
- short pulses
- full coherence

The technical solution proposed is based on a combination of advanced conventional lasers and FELs

- 2.25 GeV SC linac – this talk
- seeded harmonic cascaded FEL – N. Thompson's talk WEOD02

NLS FEL source requirements (Dec. 2008)

1. Photon energy range and tunability:

Three FELs: FEL1 @ 50-300 eV; FEL2 @ 250-850 eV; FEL3 @ **430-1000 eV**

2. Repetition rate:

1 kHz with an upgrade path to 100 kHz (or more)

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)

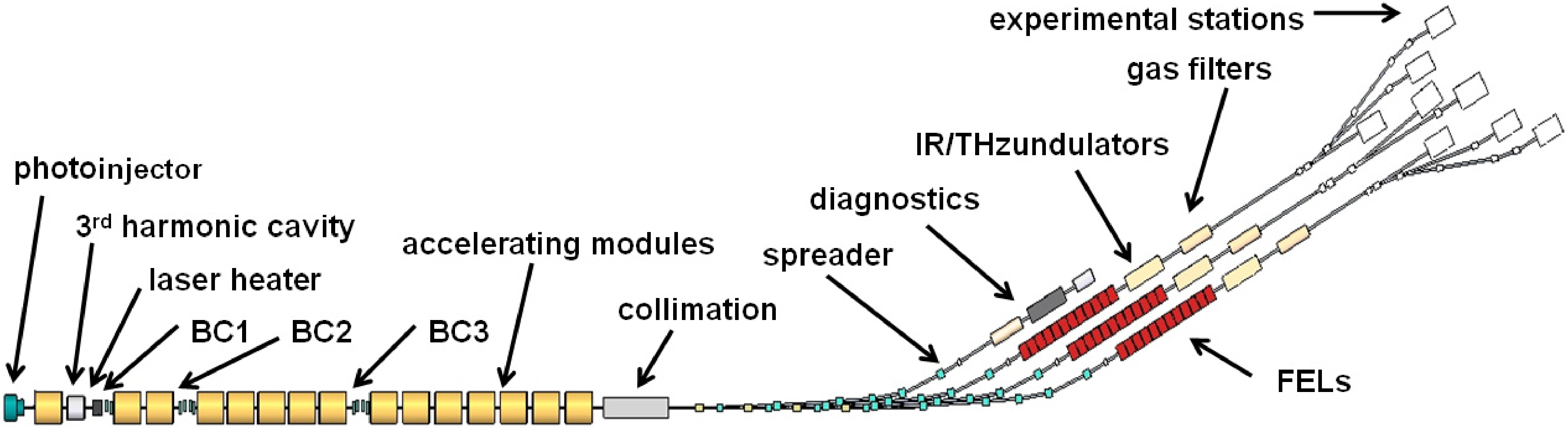
4. Transverse and longitudinal coherence

5. Polarisation:

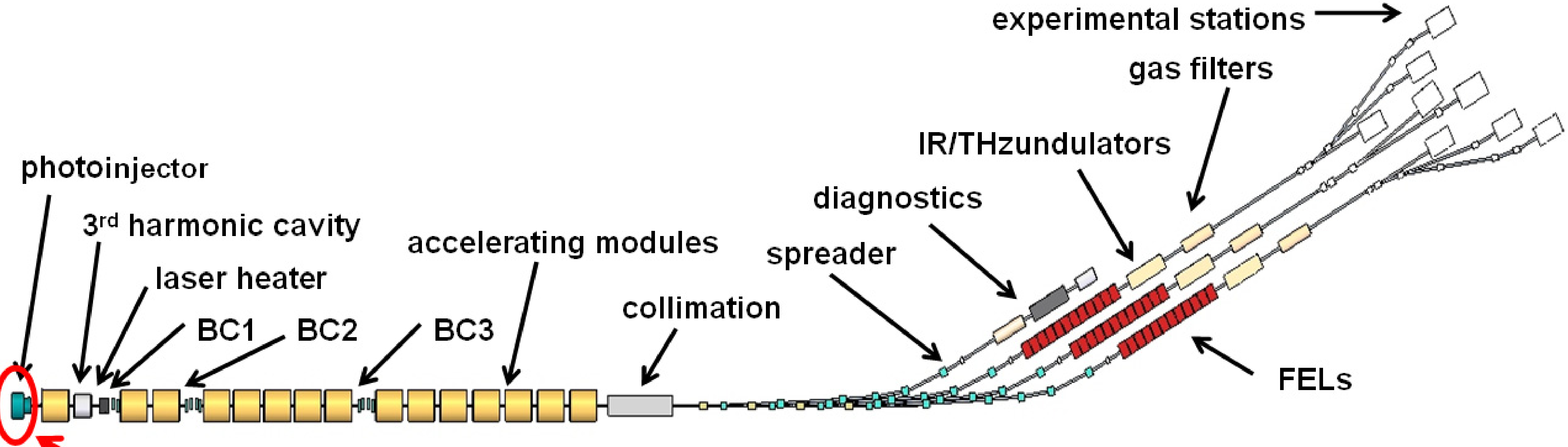
FEL1 & FEL2: complete polarisation control (arbitrary elliptical and rotatable linear).

FEL3: at least horizontal and circular (R/L) polarisation over the full range 430-1000 eV.

Layout of NLS

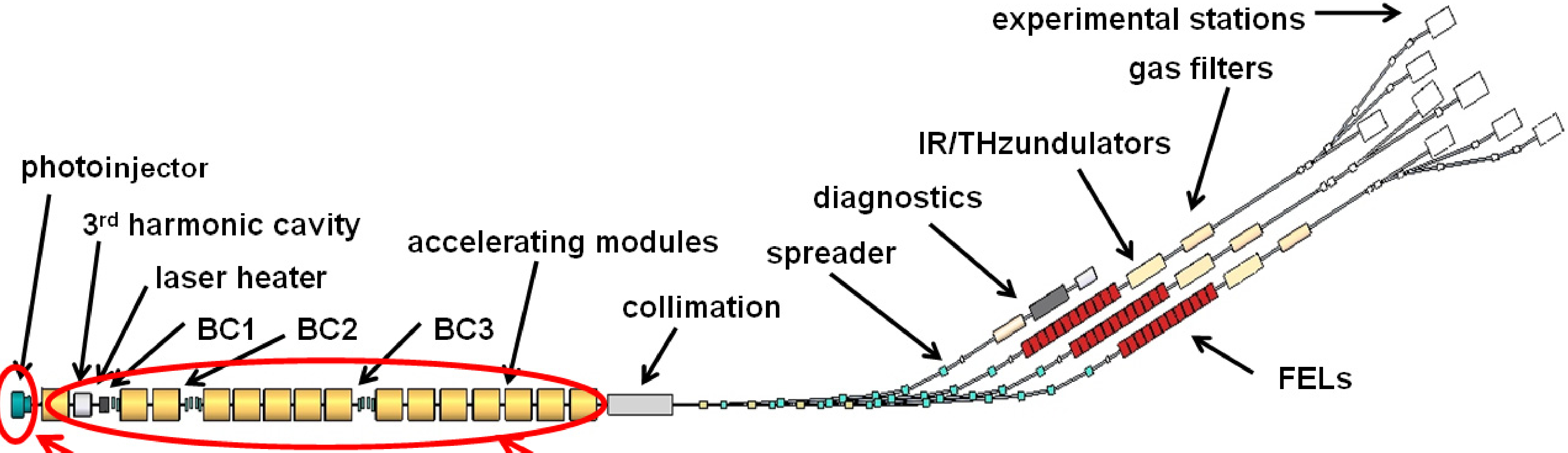


Layout of NLS



high brightness electron gun, operating (initially) at 1 kHz

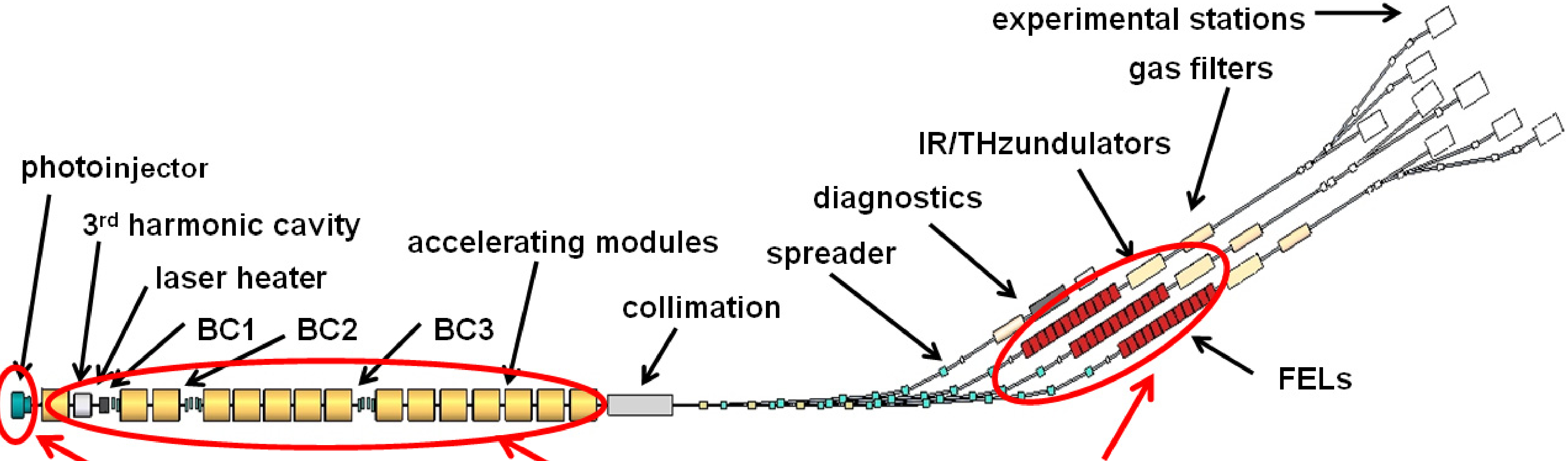
Layout of NLS



high brightness electron gun, operating (initially) at 1 kHz

2.25 GeV cw superconducting linac

Layout of NLS



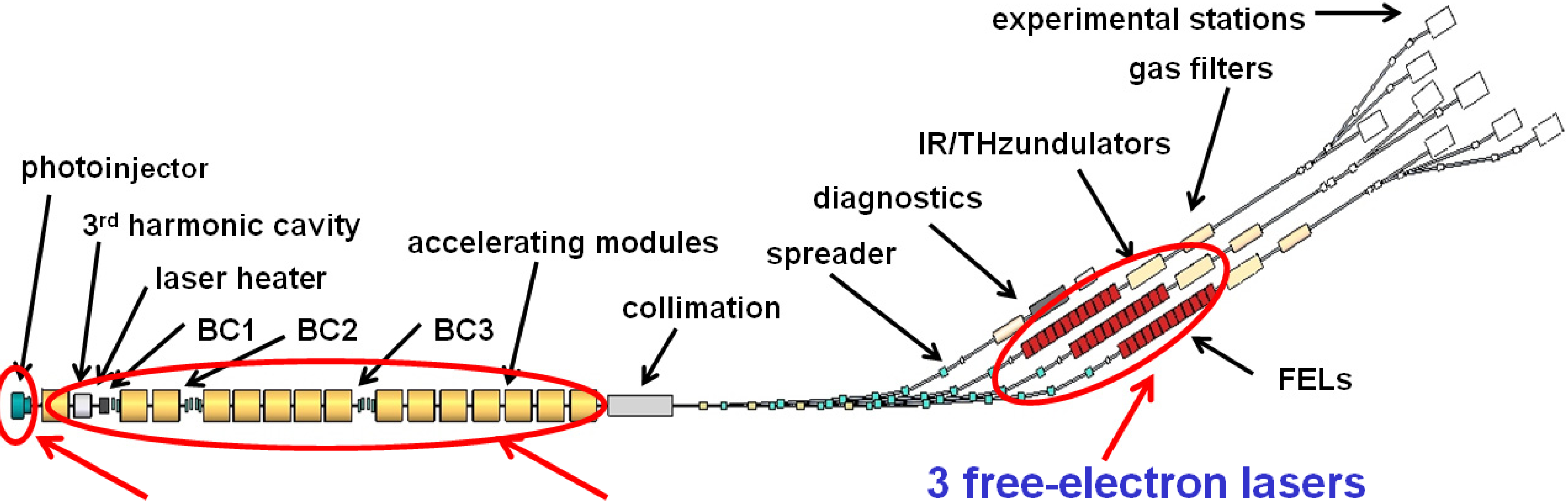
high brightness electron gun, operating (initially) at 1 kHz

2.25 GeV cw superconducting linac

3 free-electron lasers covering the photon energy range 50 eV–1 keV,

- *GW peak power*
- *20 fs pulses*
- *laser HHG seeded for longitudinal coherence*

Layout of NLS



high brightness electron gun, operating (initially) at 1 kHz

2.25 GeV cw superconducting linac

3 free-electron lasers covering the photon energy range 50 eV–1 keV,
- *GW peak power*
- *20 fs pulses*
- *laser HHG seeded for longitudinal coherence*

+ synchronised conventional lasers 60 meV – 50 eV and IR/THz sources for pump-probe experiments

Requirements on the electron beam (I)

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	1-few kA

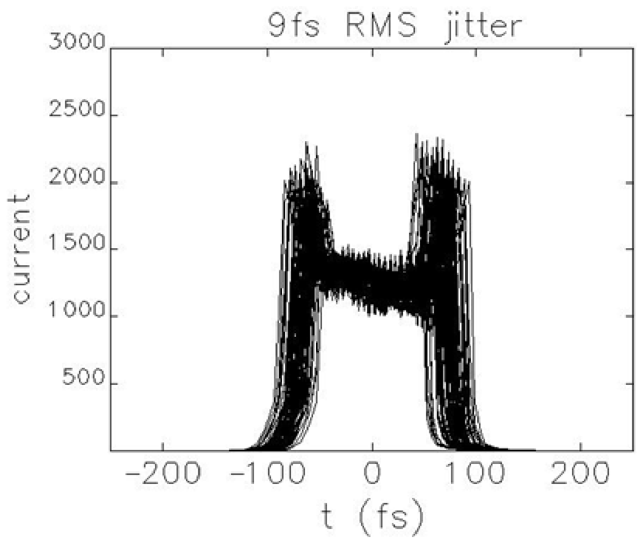
For seeded cascade harmonic generation with a 20 fs FWHM seed laser pulse we need an electron bunch with constant slice parameters over 20 fs plus the relative jitter between the electron bunch and the laser seed pulse.

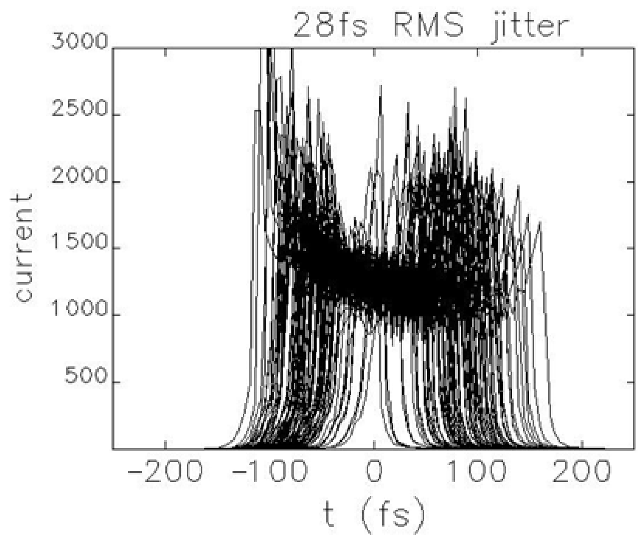
Requirements on the electron beam (I)

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	1-few kA

For seeded cascade harmonic generation with a 20 fs FWHM seed laser pulse we need an electron bunch with constant slice parameters over 20 fs plus the relative jitter between the electron bunch and the laser seed pulse.



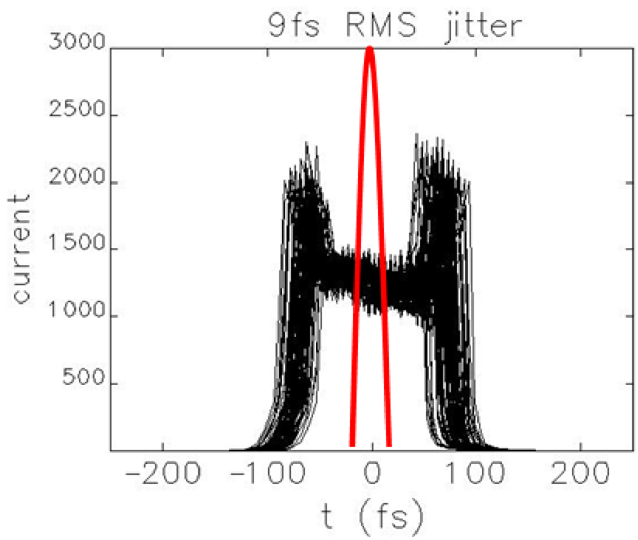


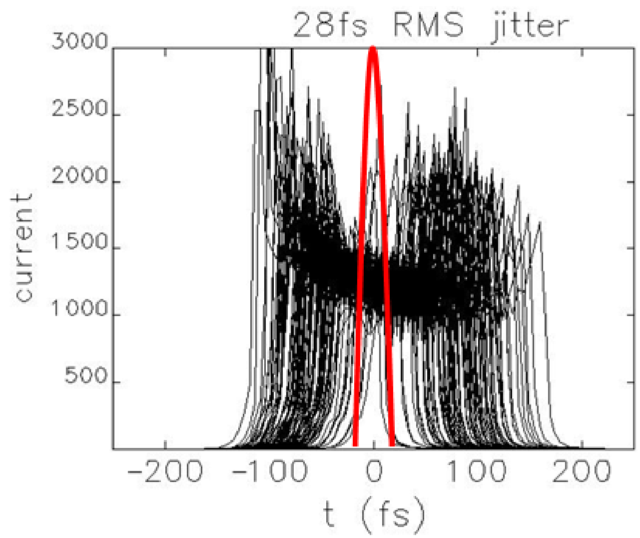
Requirements on the electron beam (I)

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	1-few kA

For seeded cascade harmonic generation with a 20 fs FWHM seed laser pulse we need an electron bunch with <u>constant slice parameters</u> over 20 fs plus the relative jitter between the electron bunch and the laser seed pulse.





Requirements on the electron beam

For seeded cascade harmonic generation

• constant slice parameters on a length of 100 fs – or longer to accommodate the seed pulse and jitter

• no jagged current distribution
• no slice offset and angle
• low sensitivity to jitter
• no residual energy chirp (or very limited)
• without accidental good slices that would spoil the contrast ratio

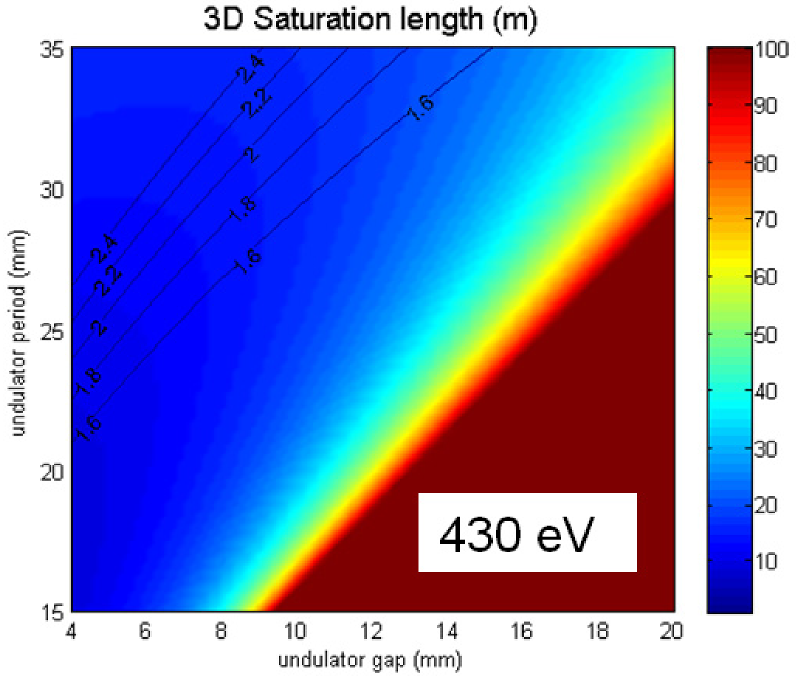
Carefully optimised RF photocathode gun and LINAC with magnetic bunch compressors can provide high brightness electron beam, but satisfying all the requirements is non trivial.

FEL working point

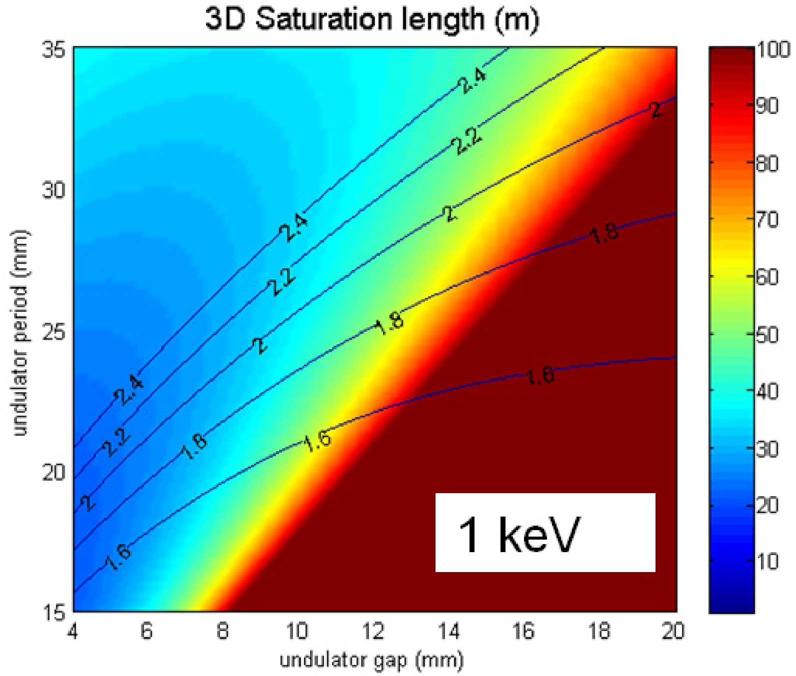
FEL working point defined by:

- 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, σ_ε = $5 \cdot 10^{-4}$



λ_u=32mm; g=8mm; K=1.6; <β >=5 m



λ_u=32mm; g=14mm; K=0.7; <β>=10m

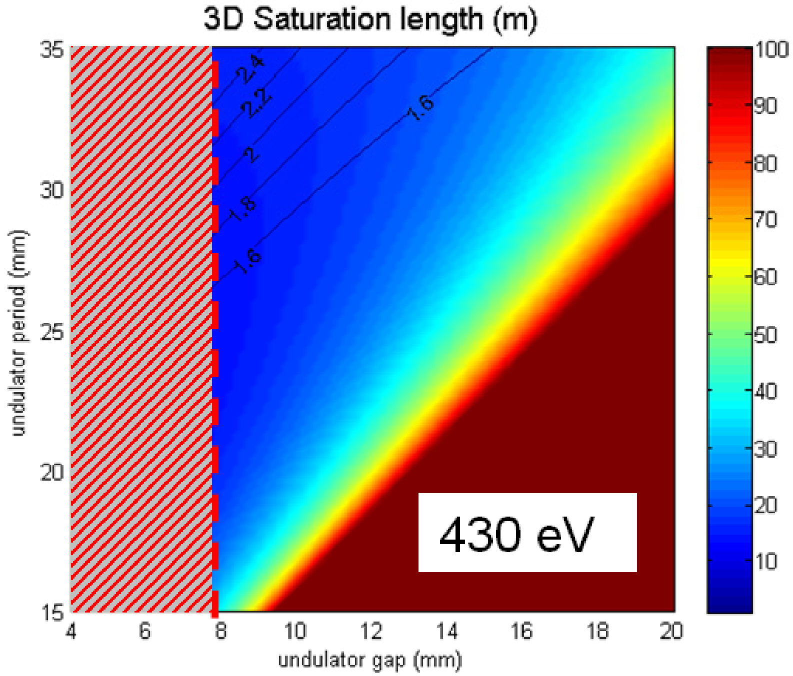
See also N. Thompson's talk – WEOD02

FEL working point

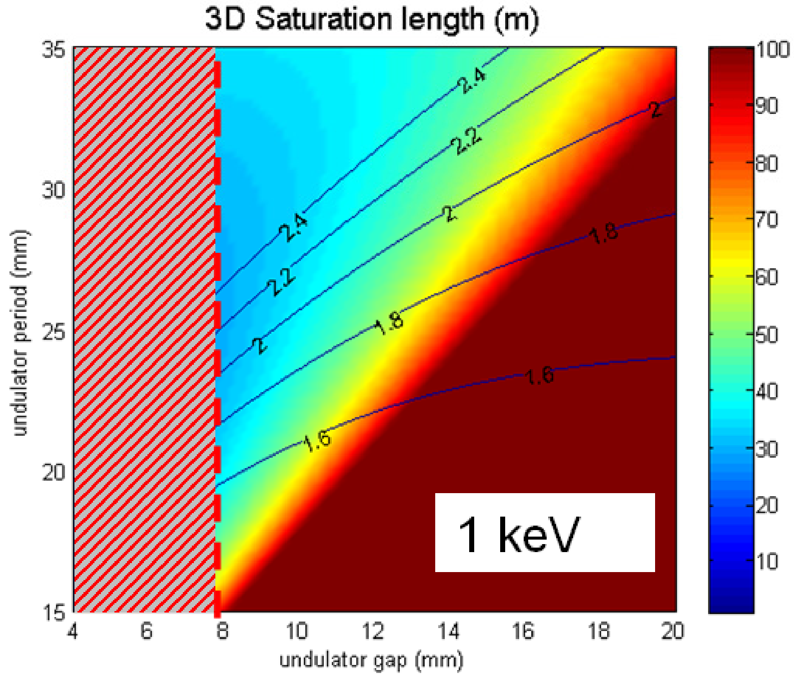
FEL working point defined by:

- 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, σ_ε = $5\cdot10^{-4}$



λ_u=32mm; g=8mm; K=1.6; <β >=5 m



λ_u=32mm; g=14mm; K=0.7; <β>=10m

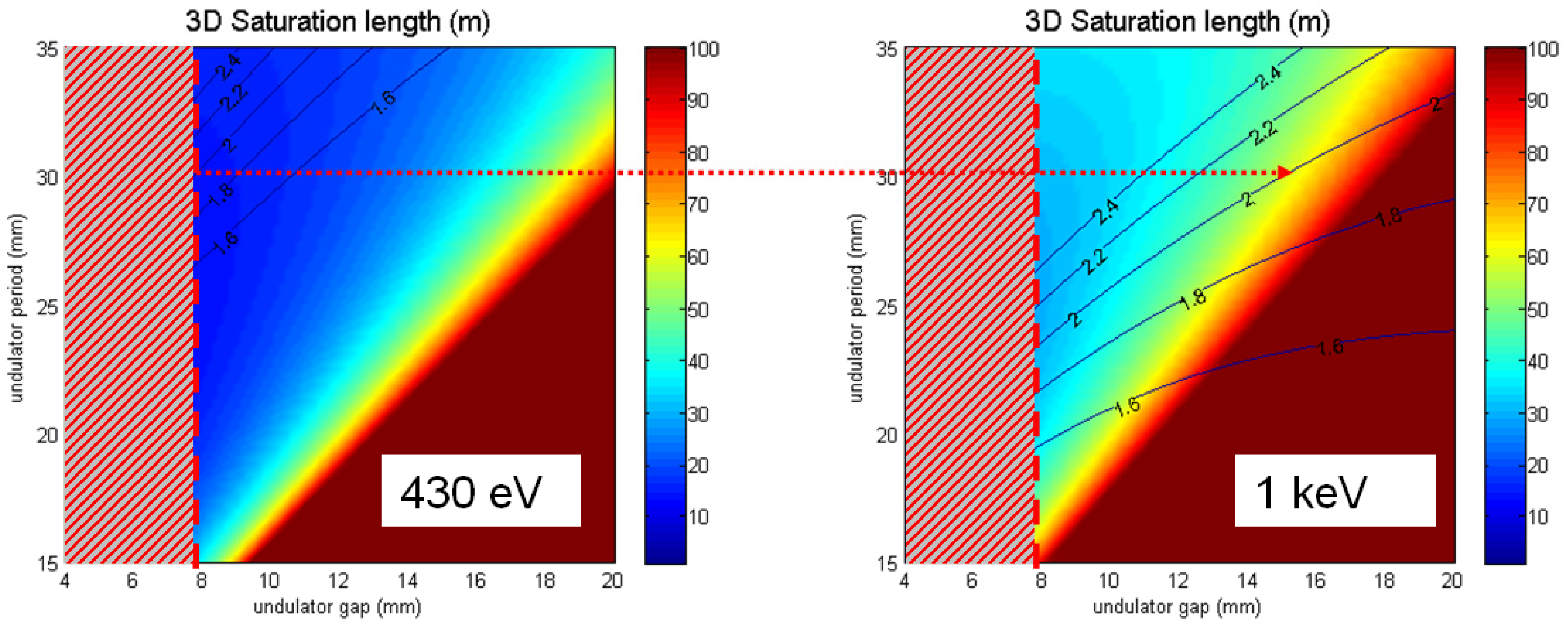
See also N. Thompson's talk – WEOD02

FEL working point

FEL 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, σ_ε = 5·10^{-4}



λ_u=32mm; g=8mm; K=1.6; <β >=5 m

λ_u=32mm; g=14mm; K=0.7; <β>=10m

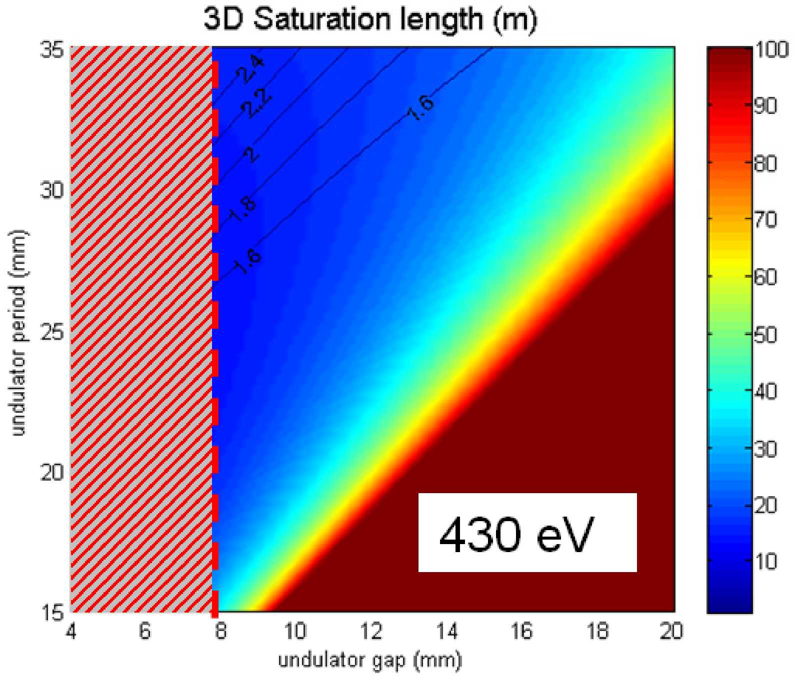
See also N. Thompson's talk – WEOD02

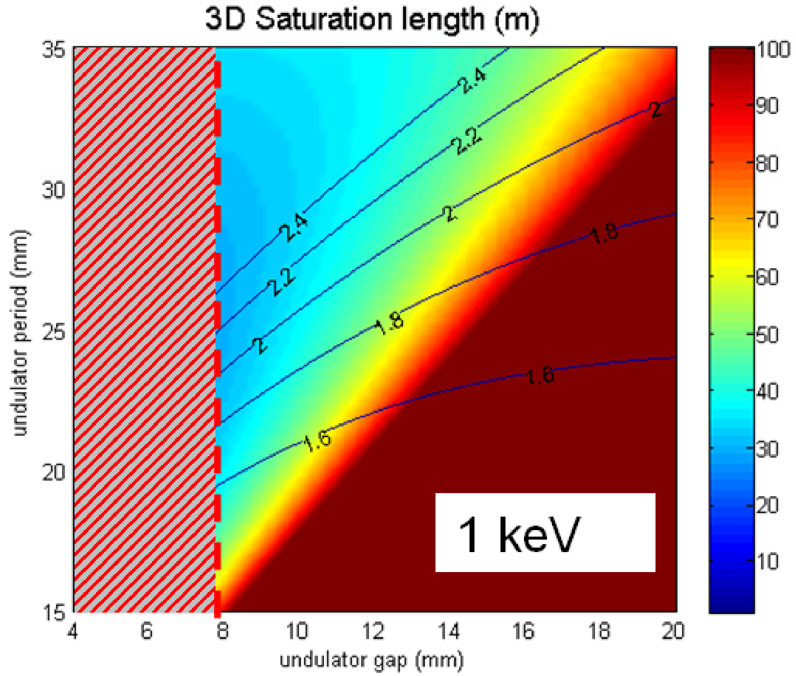
FEL working point

FEL working point defined by:

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

Using Xie parameterisation with I_{peak} = 1 kA, ε_n = 1μm, $\sigma_\varepsilon = 5\cdot10^{-4}$





λ_u=32mm; g=8mm; K=1.6; <β >=5 m

λ_u=32mm; g=14mm; K=0.7; <β>=10m

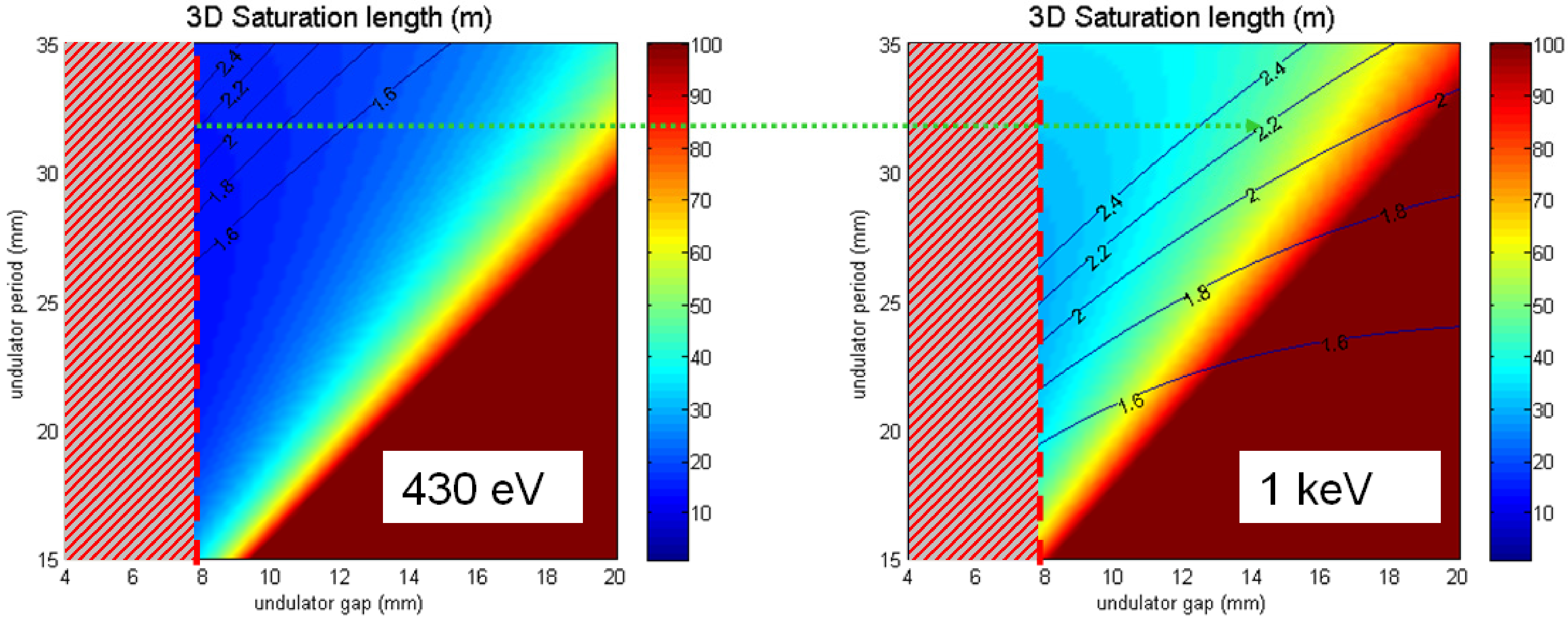
See also N. Thompson's talk – WEOD02

FEL working point

FEL 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, $\sigma_\varepsilon = 5 \cdot 10^{-4}$



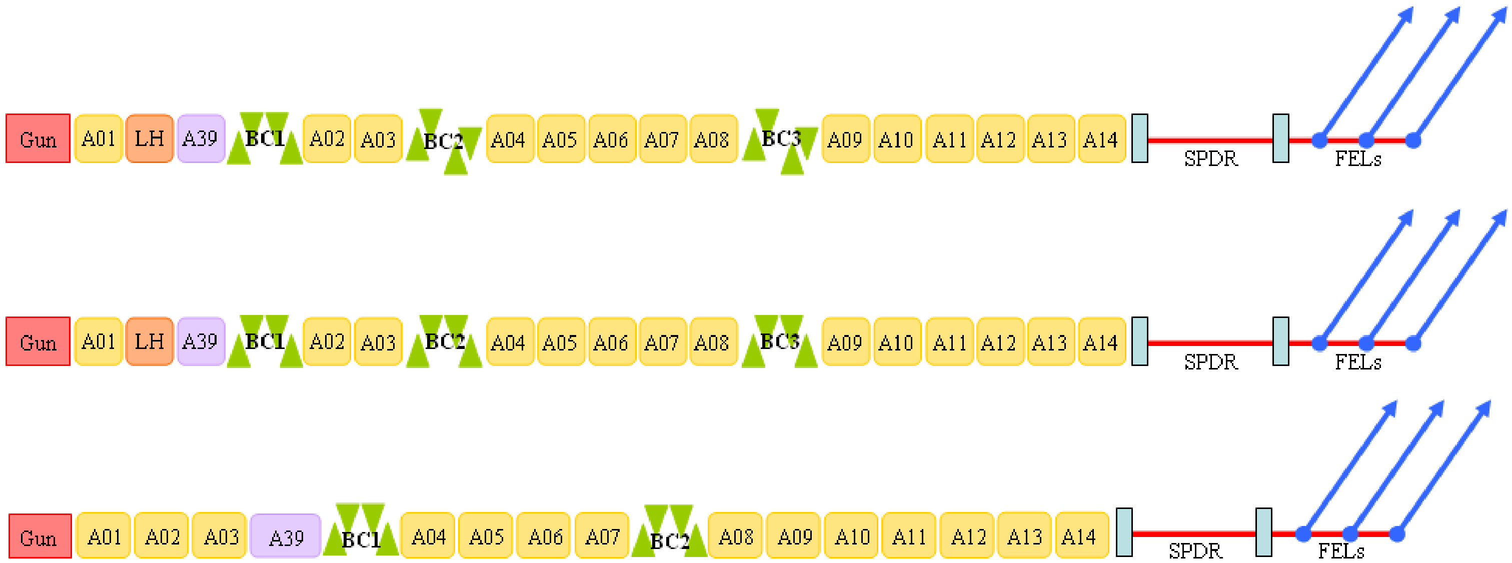
λ_u=32mm; g=8mm; K=1.6; <β >=5 m

λ_u=32mm; g=14mm; K=0.7; <β>=10m

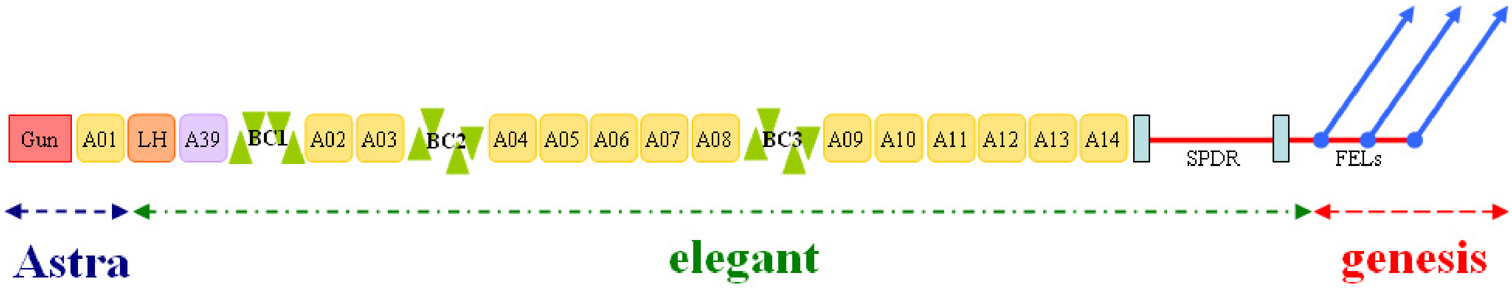
See also N. Thompson's talk – WEOD02

Layout and parameters of the 2.25 GeV linac

- 2.25 GeV; 200 pC
- optimised L-band gun → J-H. Han et al., TUPC44-45
- LINAC L-band gradient ~20 MV/m and 3HC @ 3.9 GHz ~15 MV/m
- Magnetic bunch compressors
- Beam spreader → F. Jackson et al., WEPC17
- Undulator train → N. Thompson's talk WEOD02 and J. Clarke et al. THOA03



Numerical optimisation of the 2.25 GeV linac (I)



Parameters used in the optimisation

- Accelerating section and 3HC amplitude and phase
- Bunch compressors strength

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

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

Elegant simulation include

- CSR, longitudinal space charge, wakefields in TESLA modules

Validation with full S2E simulation from GUN to FEL (time dependent mode)

Numerical optimisation of the 2.25 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;

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.

Beam quality optimisation driven directly by the required FEL performance. 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 the 2.25 GeV linac (III)

The multi-objective multi-parameter optimisation of the LINAC is based on the fast numerical computation of the Xie gain length as a function of the linac parameters for the electron bunch slices

3D 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:

$\langle L_{3D} \rangle$, $\langle P_{sat} \rangle$ over the length of the "constant slice region", …

Parameters:

amplitudes and phases of RF accelerating sections, compressors, …

Genetic Algorithm SPEA2 with Parallel Search Algorithms

Multi-objectives Multi-parameters optimisation (IV)

18000 runs with 100K particle each

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

9 parameters: amplitude and phase of ACC02-3; ACC4-8, 3HC, BC1-3

Manual optimisation (red dot)

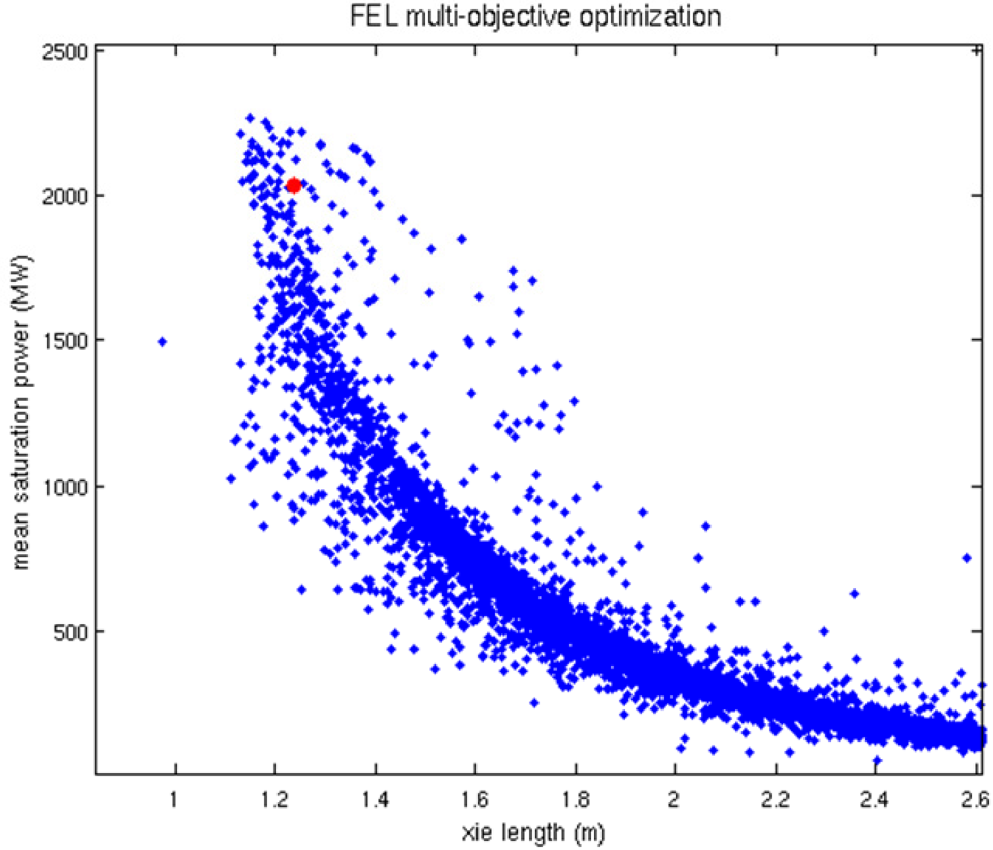
xie length 1.24 (m)

avg sat power 2030 (MW)

Multi-objective optimisation

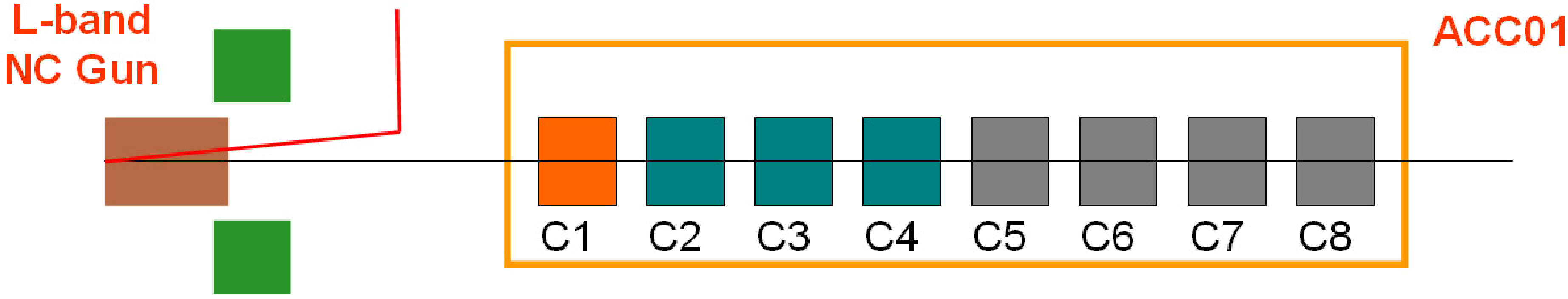
xie length 1.15 (m) (–8%)

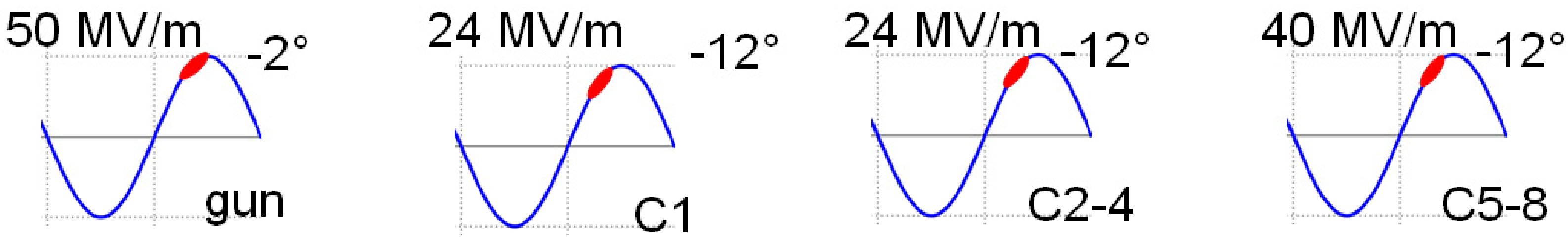
avg sat power 2220 (MW) (+11%)



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

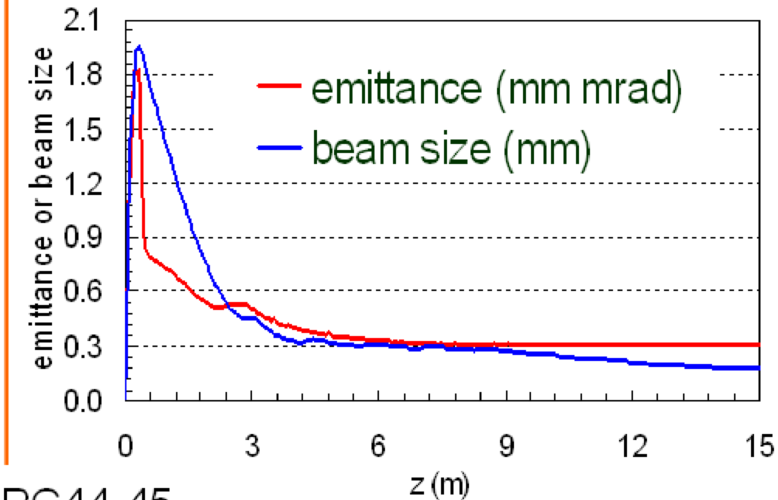
Optimised beam from the Injector





Parameters used in the optimisation:

- amplitude and phase of RF gun cavity
- amplitude and phase of ACC01
- solenoid field
- position of solenoids and ACC01



courtesy J.H. Han – TUPC44-45

Optimised beam from the L-band gun

L-band NC gun optimisation

ASTRA to deal with space charge issues

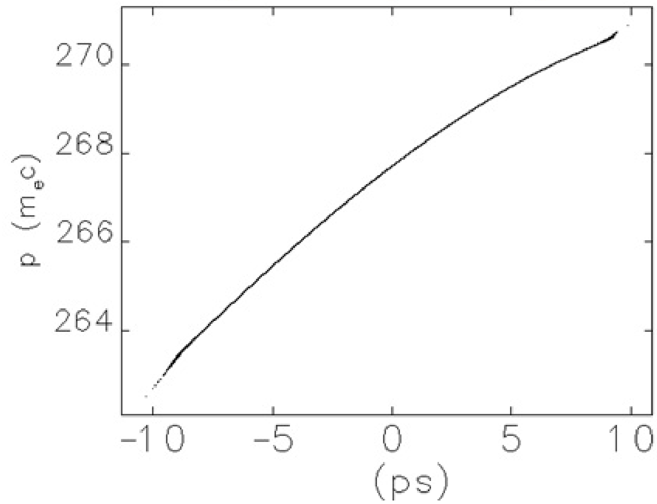
200 pC – 18 ps FW – 130 MeV

Normalised slice emittance about $3 \cdot 10^{-7}$ m

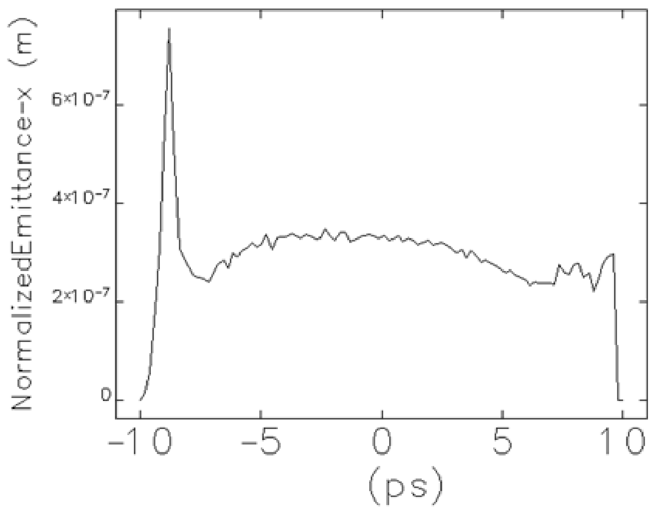
Slice relative energy spread below $2 \cdot 10^{-5}$

I peak ~ 14 A

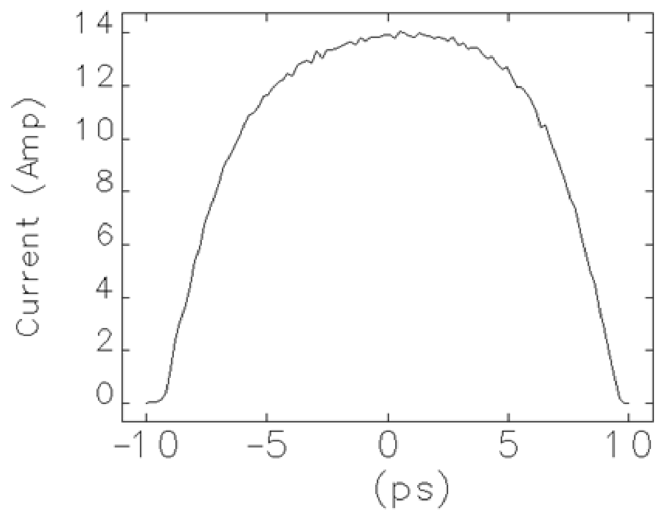
Longitudinal phase space



Slice normalised emittance

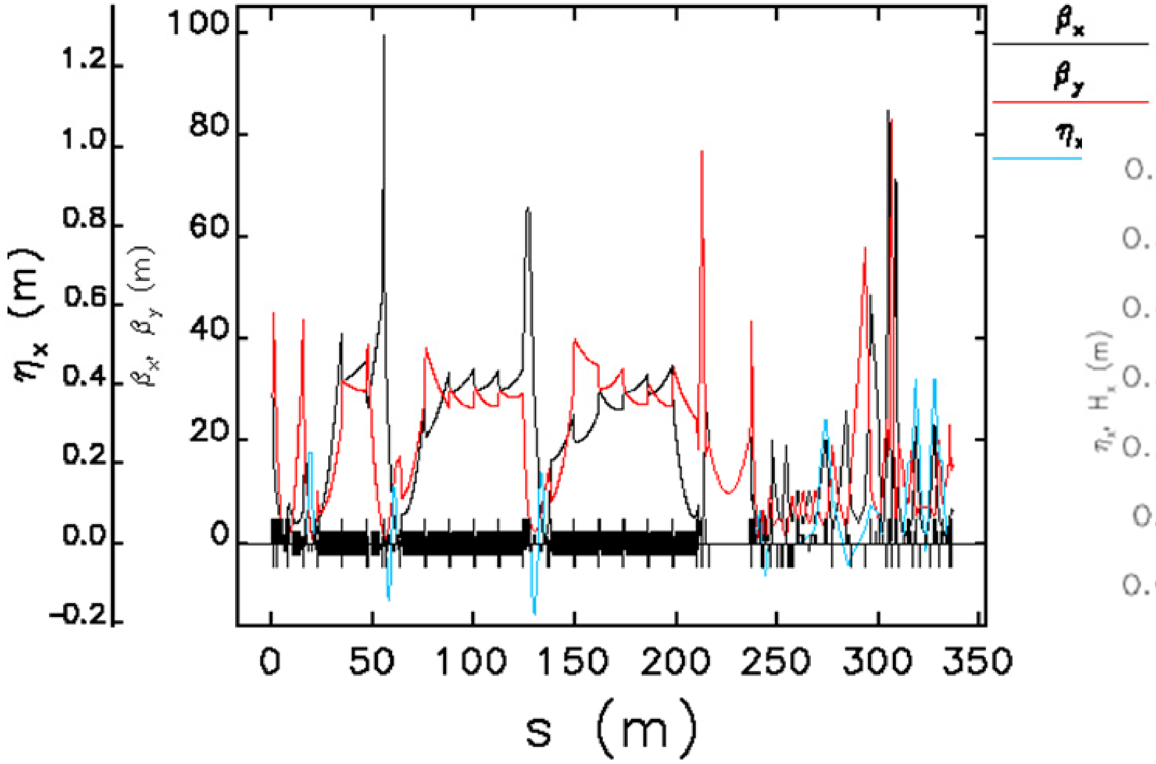


Longitudinal current distribution

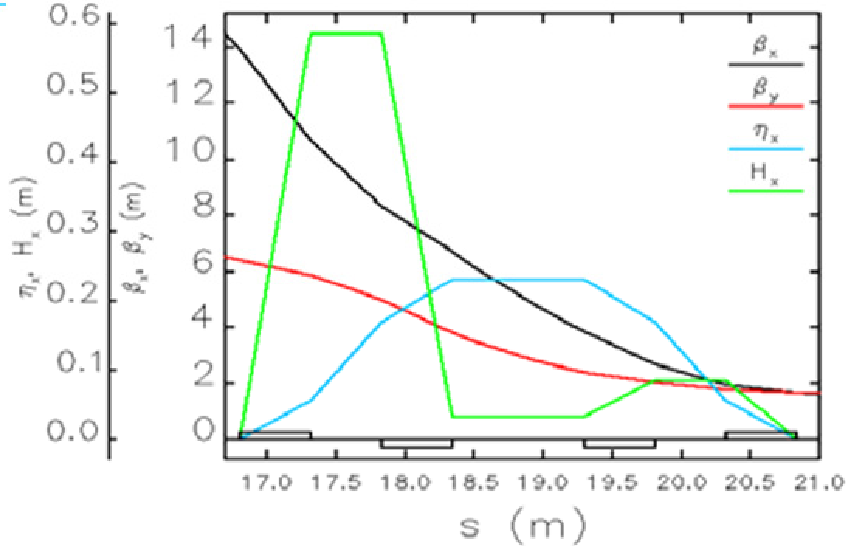


courtesy J.H. Han – TUPC44-45

Linac optics functions



Twiss parameters for nlsl_0p2nC_schic

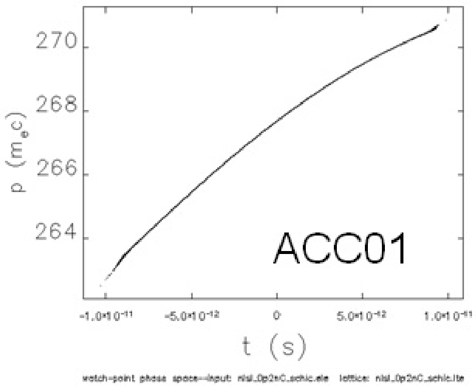


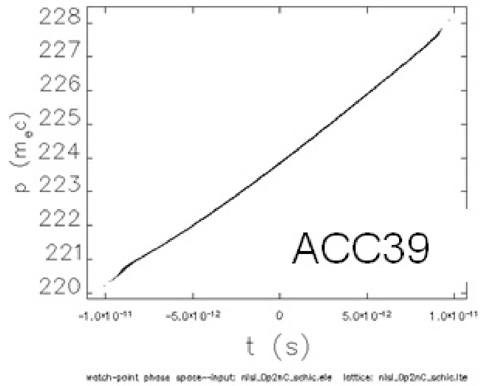
One C-chicane and two S chicanes with 4 dipoles; minimum β_x at dipole 4

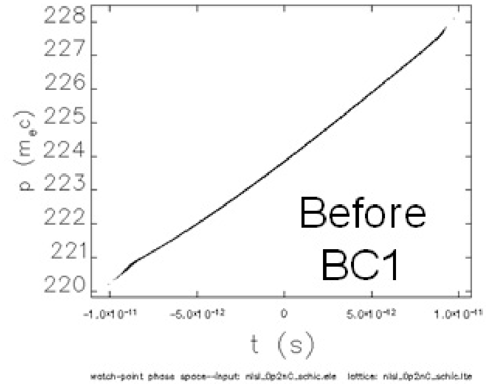
Spreader based on LBNL TBA design added sextupoles to control CSR

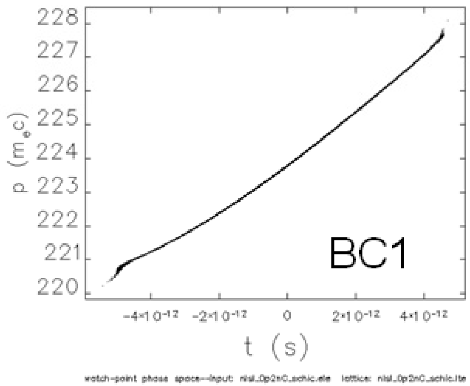
F. Jackson et al., WEPC17

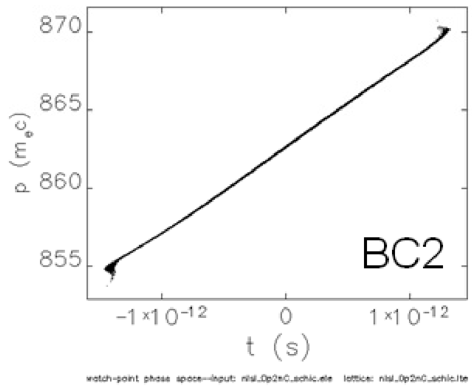
Beam evolution along the linac: 2M particle tracking

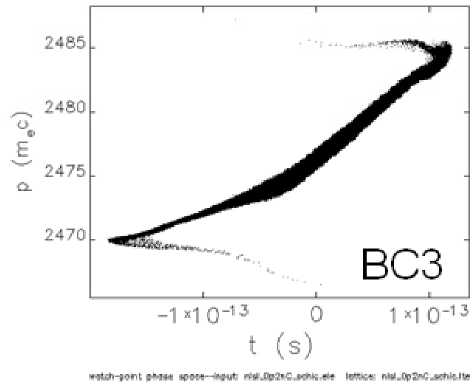


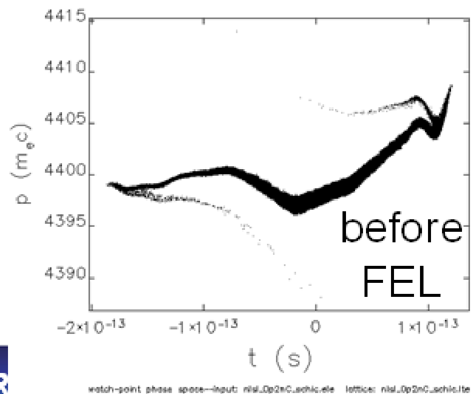












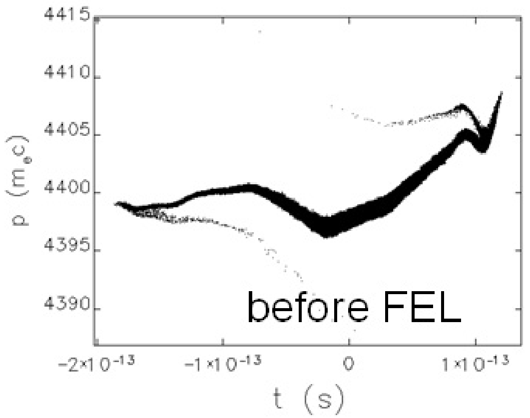
18 ps FW at start

9 ps FW at 115 MeV — compression ratio 2

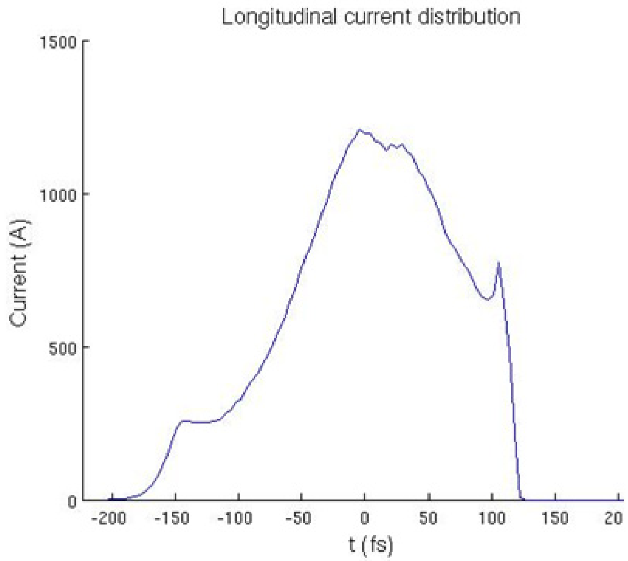
3 ps FW at 440 MeV — compression ratio 3

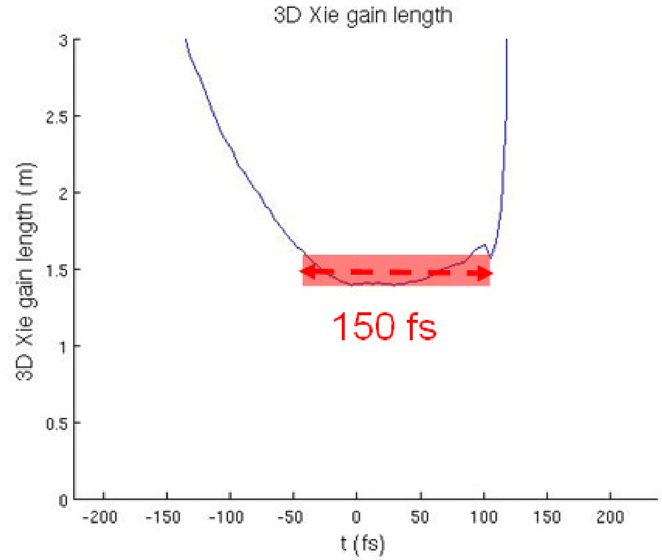
250 fs FW at 1.26 GeV — compression ratio 12

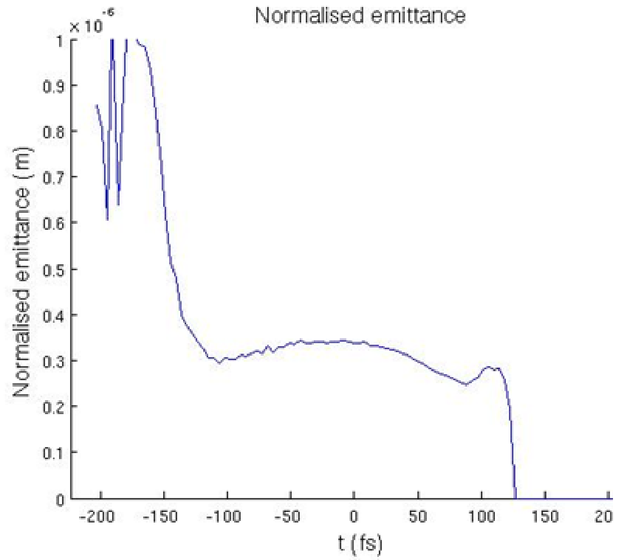
Slice analysis of electron beam at the FEL

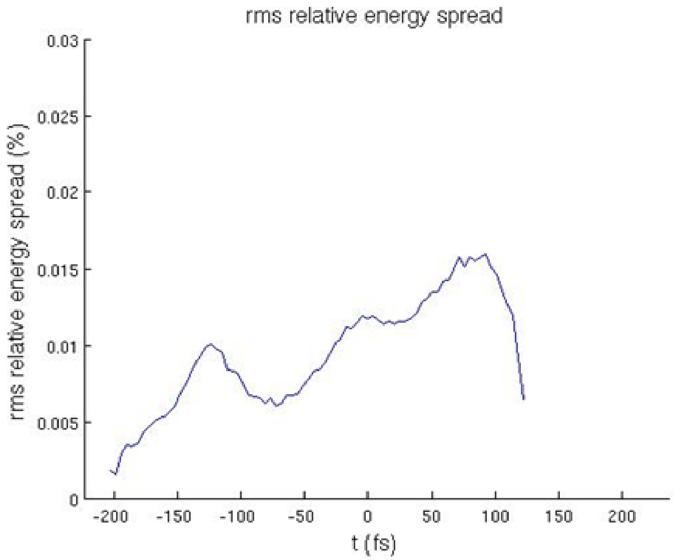


BC1	-82.5 mm
BC2	-112 mm
BC3	-104 mm
Ph 2-3	10°
Ph 4-8	5°
Ph 3HC	181°
V RF	20 MV/m
V 3HC	8.1 MV/m









Energy chirp issue

Time dependent simulations in the seeded harmonic cascade schemes will assess the acceptable energy chirp. Indicatively the energy chirp should be smaller than the SASE intrinsic BW ($\sim\rho=10^{-3}$). To reduce the energy chirp

- use wakefields;

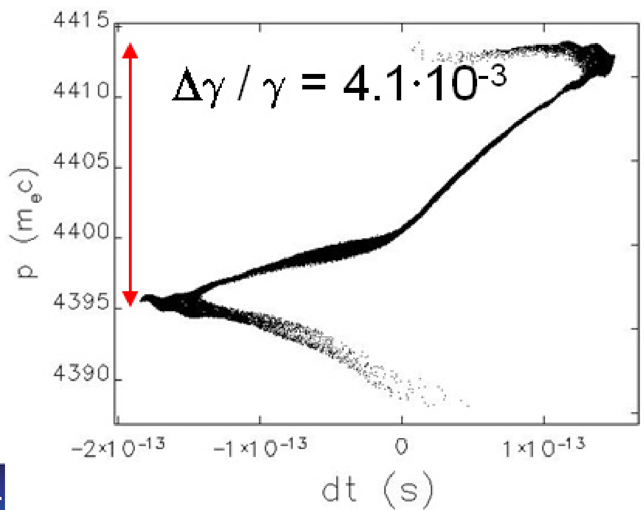
  in L–band structures wakefields are weaker than in S-band; 200 pC is too small

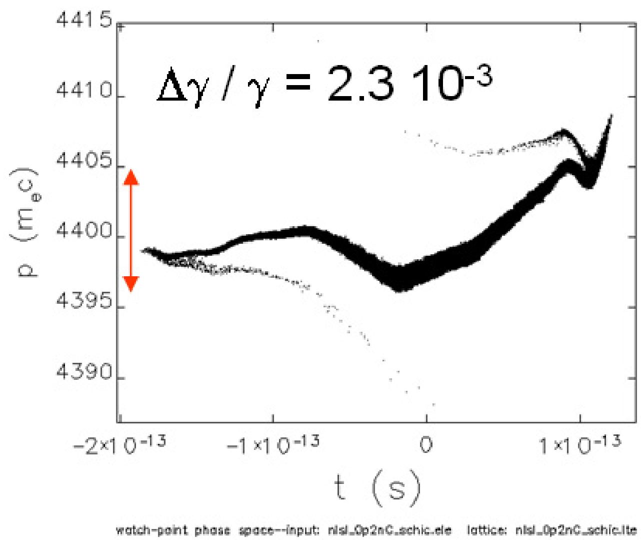
- use the main RF to reduce chirp accelerating "beyond crest"

  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



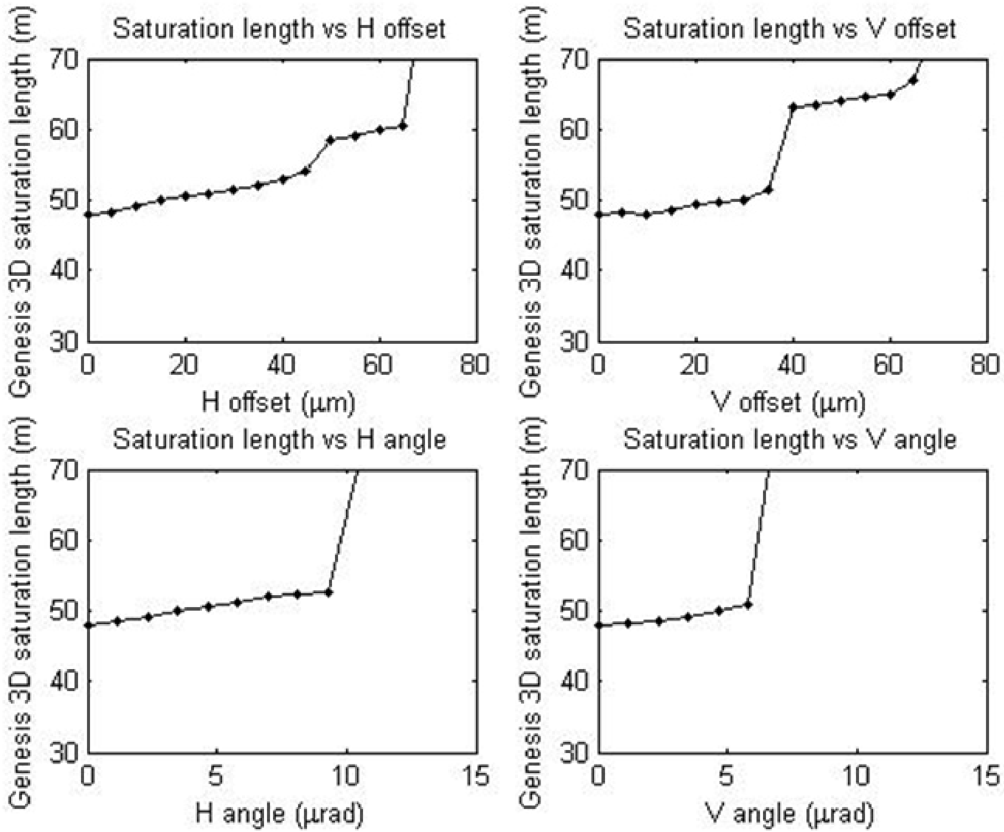


S-Chicanes vs C-Chicanes: slice angle and offset (I)

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

<u>ideal undulator train</u>;

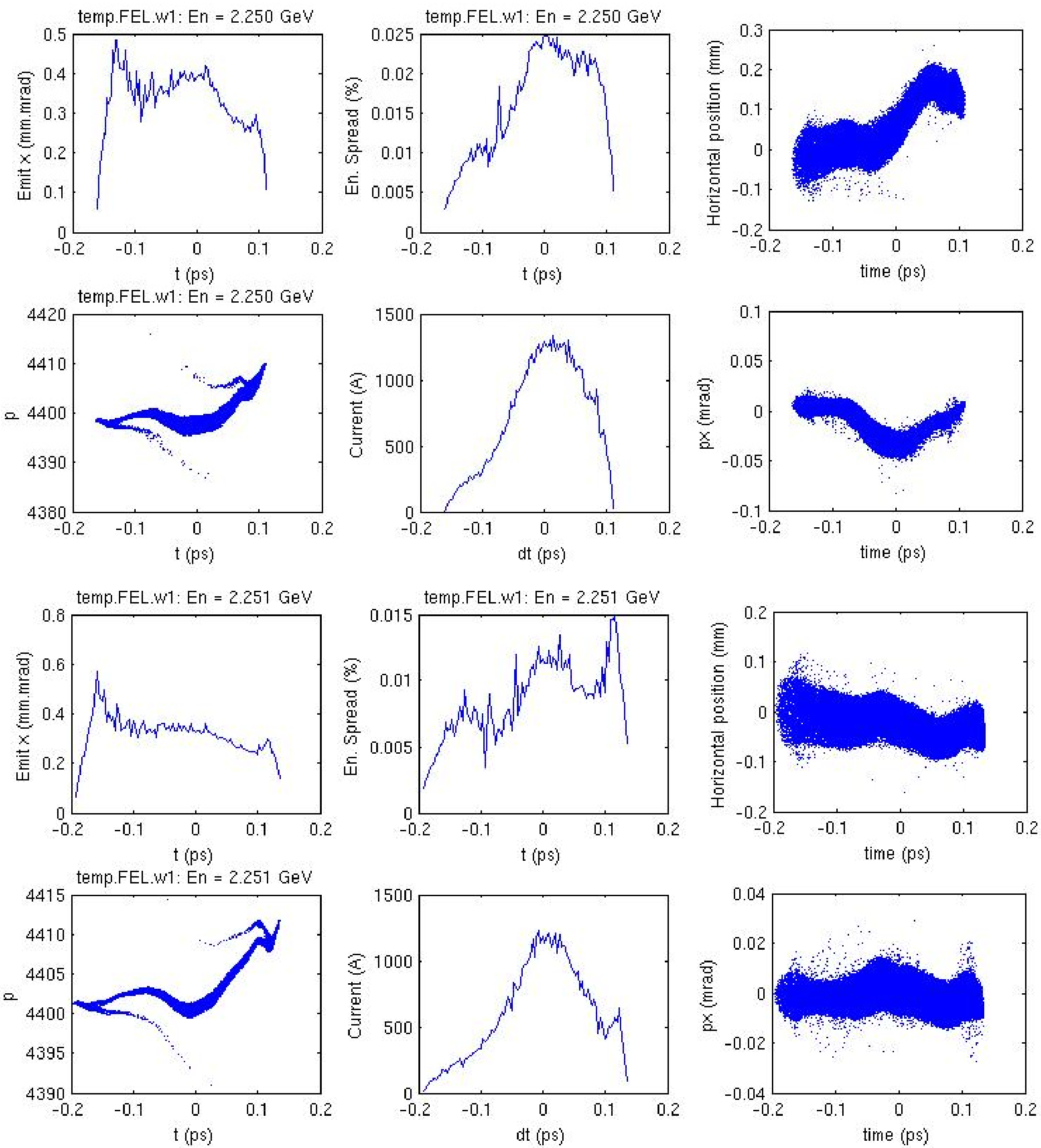
(normalis. emitt. ε_x = 0.4 um, relative energy spread 2e-4, I peak = 1.2 kA)



Angle dependence is very critical

Included in the optimisation of the LINAC by taking into account the effect of angle and offset in the modified 3D Xie gain length

S-Chicanes vs C-Chicanes: slice angle and offset (II)



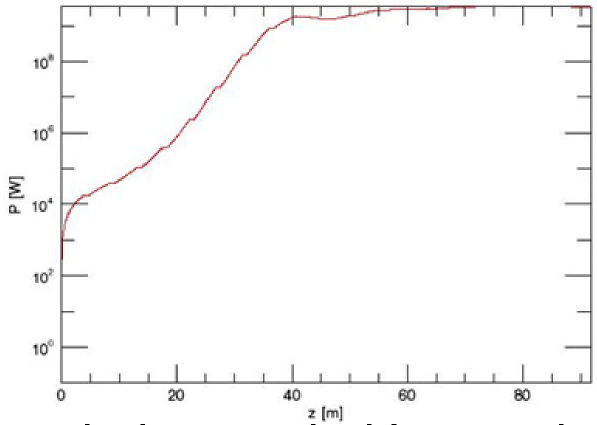
The angle and offset in the slices with the C-type chicanes is

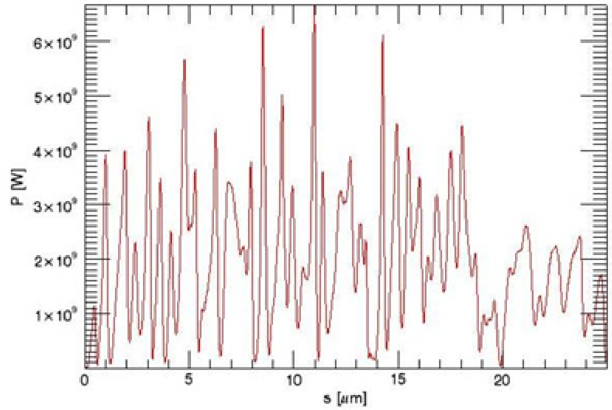
almost 200 μm and 50 μrad

With S-type chicanes this is significantly corrected while keeping a good slice emittance, slice energy spread and peak current

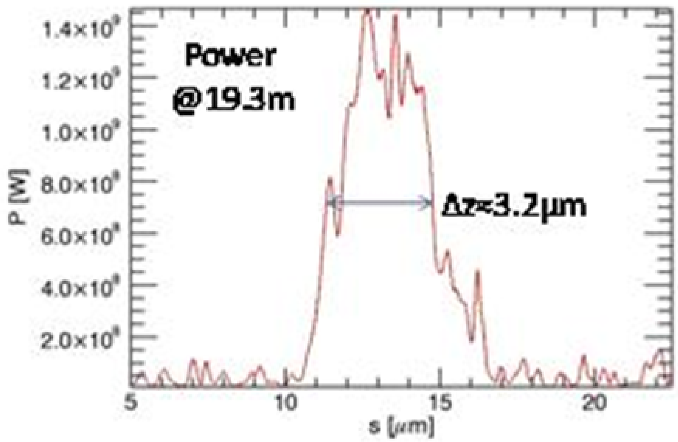
FEL time dependent simulations

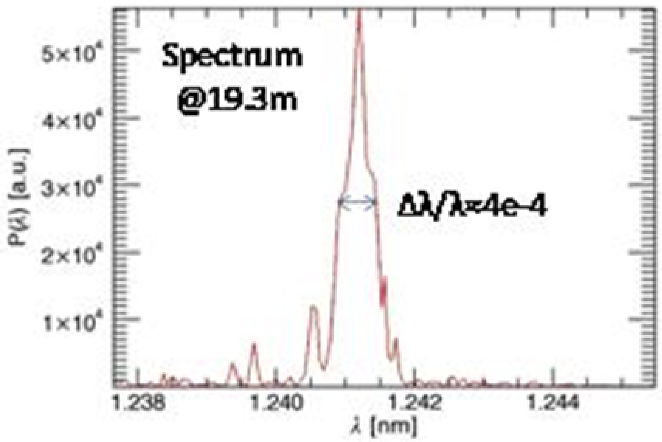
FEL SASE time dependent simulations confirm the good slice beam quality achieved in the optimisation





The seeded cascaded harmonic scheme generates a 20 fs pulse with good temporal quality (time bandwidth product ~ 1; contrast ratio 15)





Courtesy N. Thompson – WEOD02

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

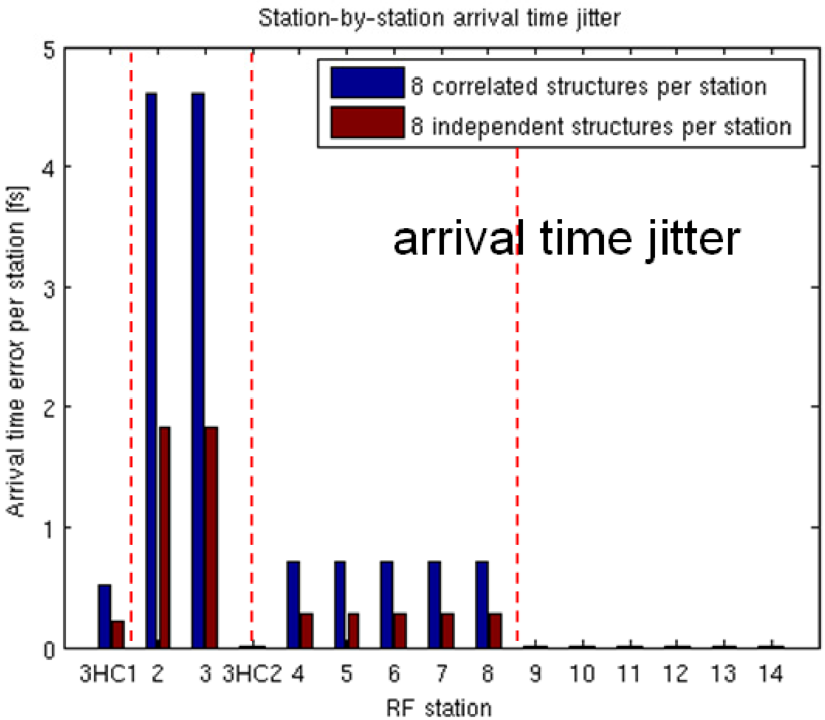
Independently powering each cavity in the RF modules

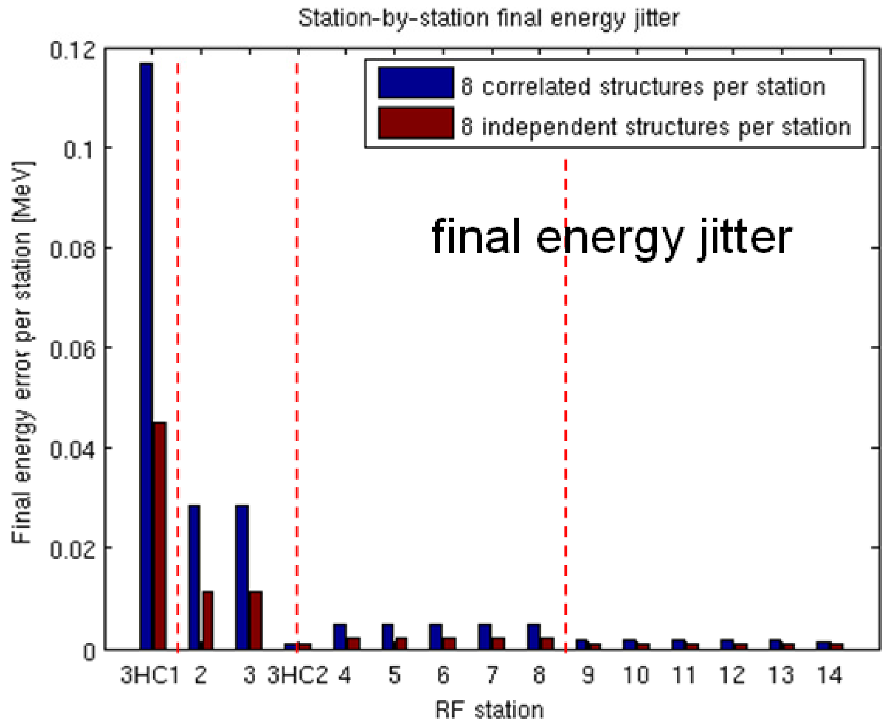
Amplitude and phase jitter applied to each cavity in the linac one by one.

The jitter in the linac is dominated by the cavities before the first bunch compressors. Cavities after BC3 play little role on jitter

Assuming the 8 cavities in each cryomodule are uncorrelated the jitter is significantly reduced

Phase (P)	0.01 degrees
Voltage (V)	1-e4 fractional





Electron beam jitter sources and results

Gun Jitter Parameters (rms)

Solenoid Field	0.02e-3	T
Gun Phase	0.1	degrees
Gun Voltage	0.1%	
Charge	1%	
X Offset	0.025	mm

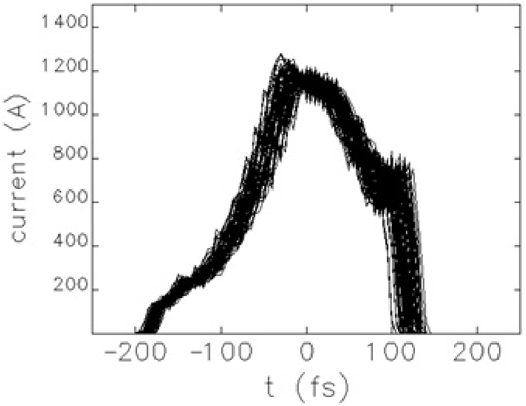
Main linac cavities

Phase (P)	0.01 degrees
Voltage (V)	1-e4 fractional
Bunch Compressors (B)	5e-5 fractional

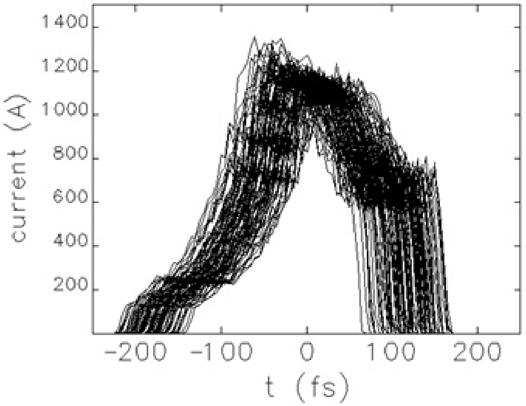
RF gun (P and V)	7 fs
Injector (RF gun + ACC01)	**21 fs**
Main linac RF P	3 fs
Main linac RF V	9 fs
BCs power supplies	**20 fs**
P + V + B combined	20 fs
P + V + B + I combined	**30 fs**

The injector (I) includes gun and first accelerating module ACC01
The ACC01 dominates the Injector jitter which dominates the whole linac jitter

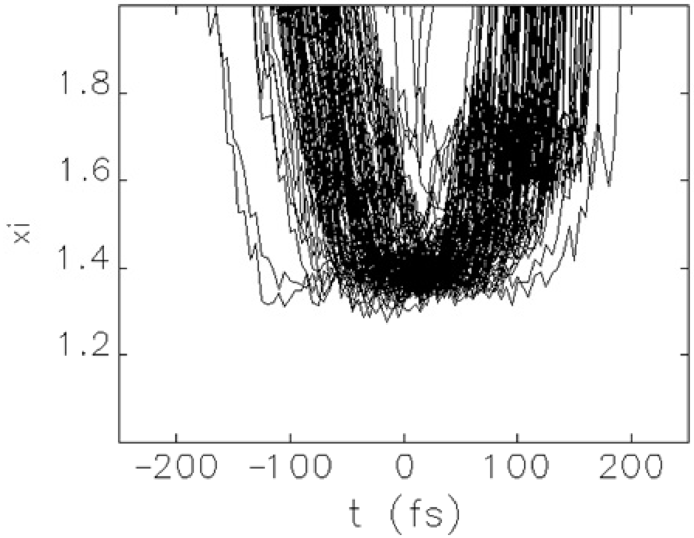
Longitudinal current profile jitter



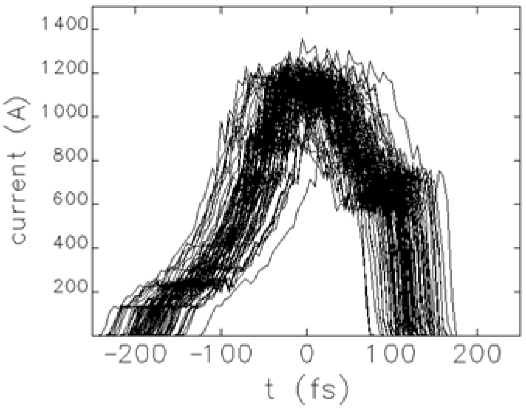
RF gun; 7 fs rms



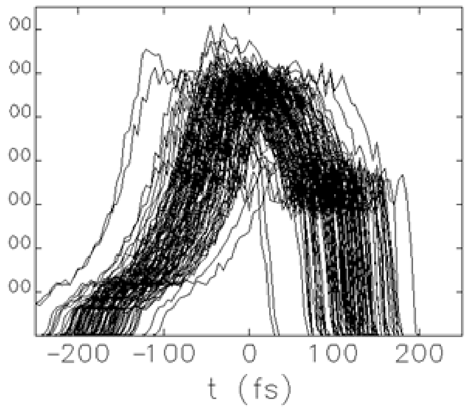
RF gun + ACC01; 21 fs rms



A significant number of pulses will miss the good region with constant slice parameters



all linac wo injector; 20 fs rms



all linac: 30 fs rms

Electron beam jitter sources and results

Reducing the two main contributors to the jitter by

- independently powering the RF cavities in ACC01
- reducing the power supply jitter in the bunch compressors to 10^{-5}

Gun Jitter Parameters (rms)

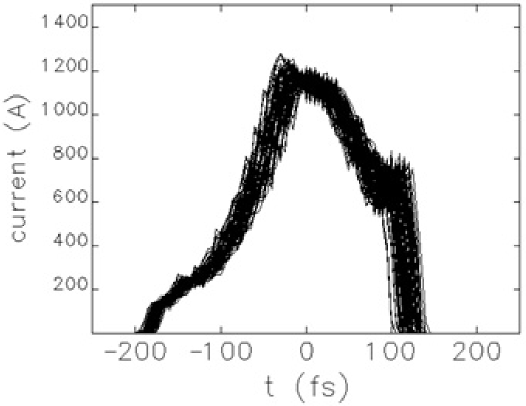
Solenoid Field	0.02e-3	T
Gun Phase	0.1	degrees
Gun Voltage	0.1%	
Charge	1%	
X Offset	0.025	mm

Main linac cavities with split ACC01

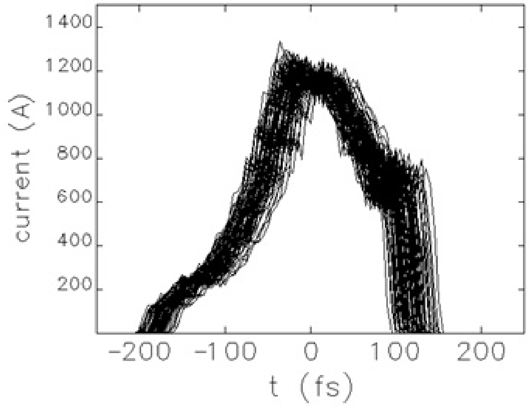
Phase (P)	0.01 degrees
Bunch Comp. (B)	1e-5 fractional
Voltage (V)	1-e4 fractional

RF gun (P and V)	7 fs	7 fs
Injector (RF gun + ACC01)	**21 fs**	**11 fs**
Main linac RF P	3 fs	3 fs
Main linac RF V	9 fs	9 fs
BCs power supplies	**20 fs**	**4 fs**
P + V + B combined	20 fs	10 fs
P + V + B + I combined	**30 fs**	**14 fs**

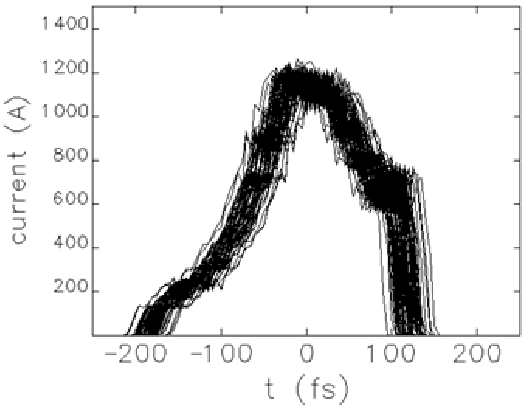
Electron beam jitter sources and results



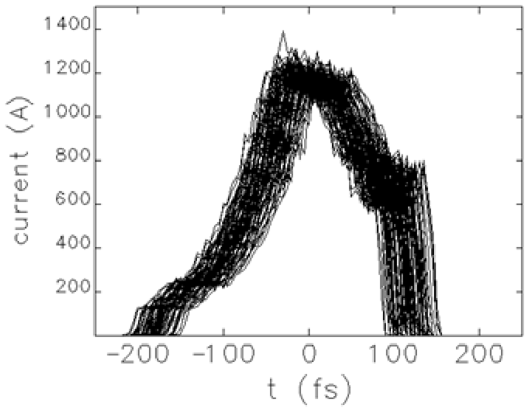
RF gun: 7 fs rms



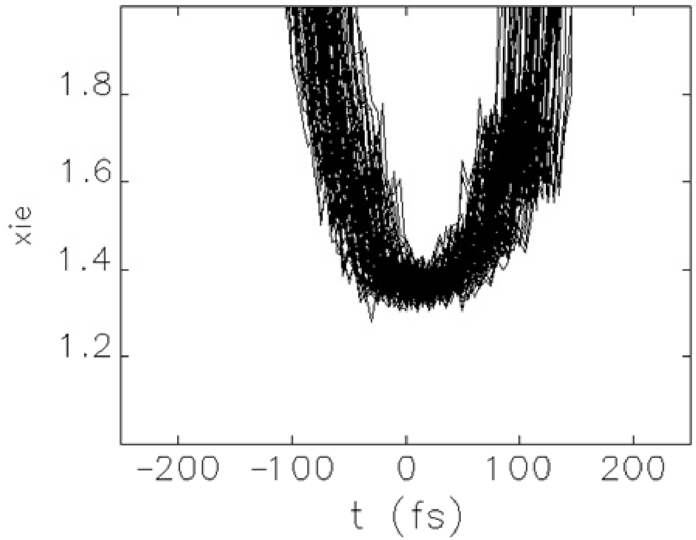
RF gun + ACC01: 11 fs rms



linac wo injector: 10 fs rms



all linac: 14 fs rms



The 3D Xie length computed for each slice has a has flat area that can accomodate the 20 fs seed laser pulse

Single spike operation

2 pC – 12 ps FW at Injector

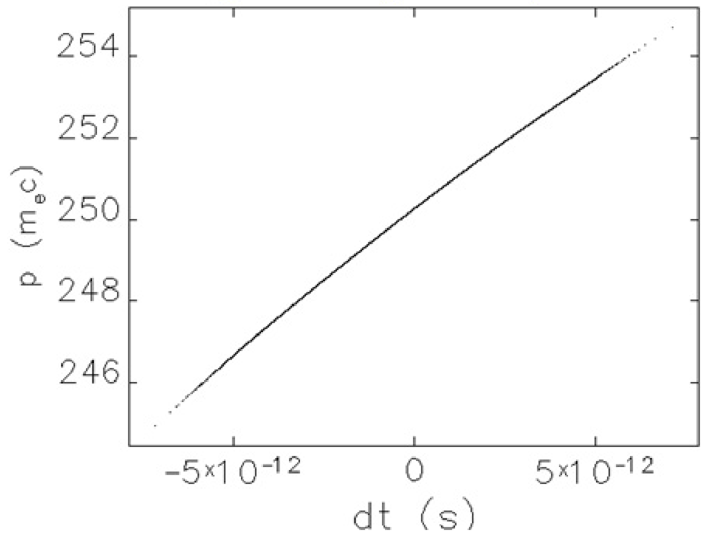
Normalised slice emittance well below 10^{-7} m

Slice relative energy spread $2 \cdot 10^{-5}$

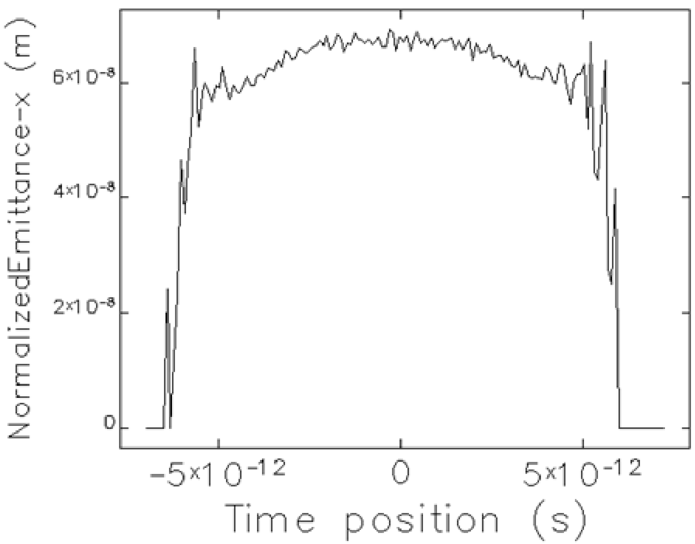
I peak > 1 A

Not too dissimilar to LCLS studies with 1 pC (0.04 – 0.09 μm)

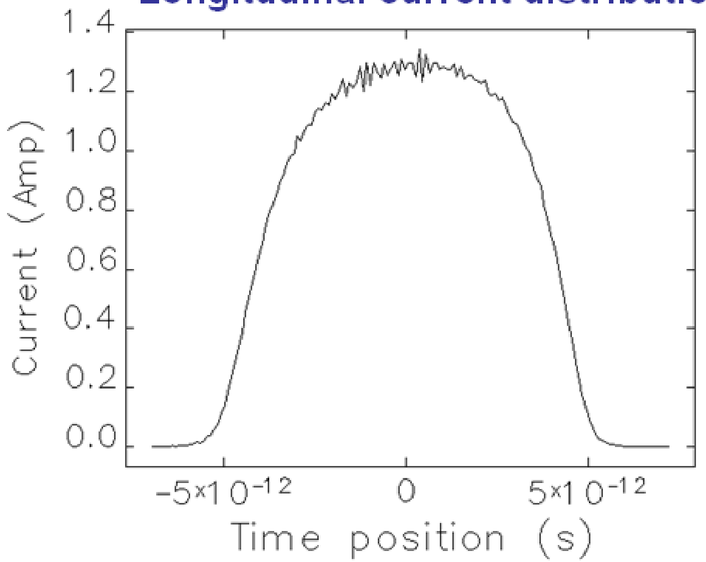
Longitudinal phase space



Slice normalised emittance



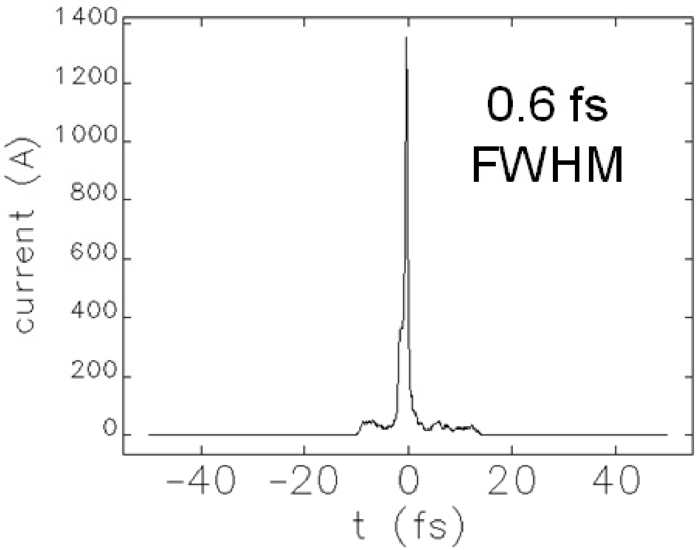
Longitudinal current distribution

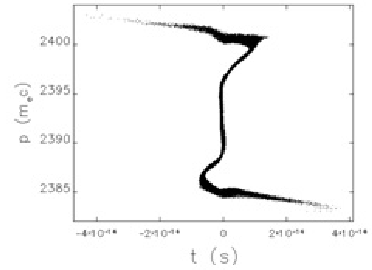


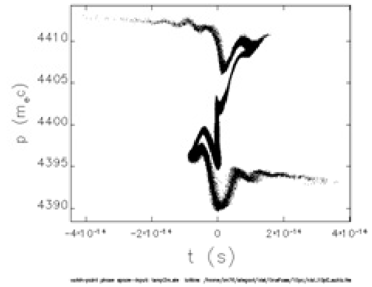
Single spike operation at 1 keV with 2 pC

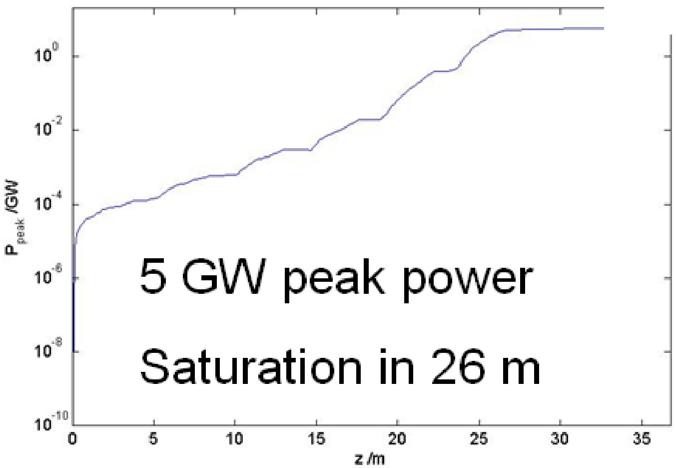
When the bunch length σ_z is smaller than $2\pi L_c$ the FEL emission occurs in a single spike temporally coherent (Bonifacio et al., PRL (1994))

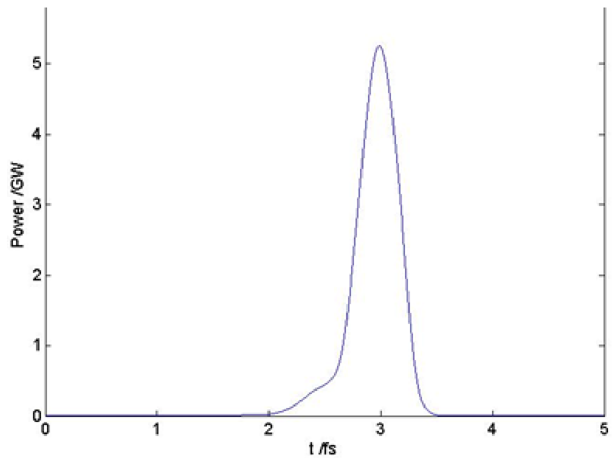
To operate in the single spike regime the bunch length must be shorter than 1 fs











Δt = 420 as;

$\Delta\lambda$ = 0.006 nm; $\Delta\lambda/\lambda$ = 0.5%

$\Delta f \, \Delta t \sim$ 0.51

$\rho \sim 1.6 \cdot 10^{-3}$ (Lsat = 27m)

$1.2 \cdot 10^{10}$ ppp @ 1 keV

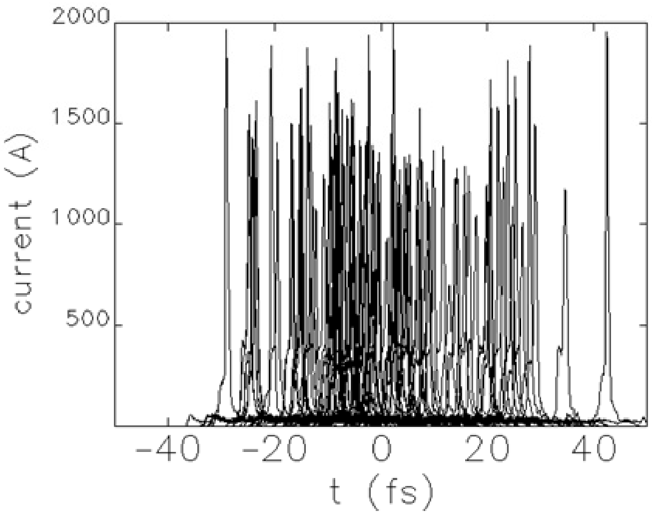
Linac jitter in single spike operation at 2 pC

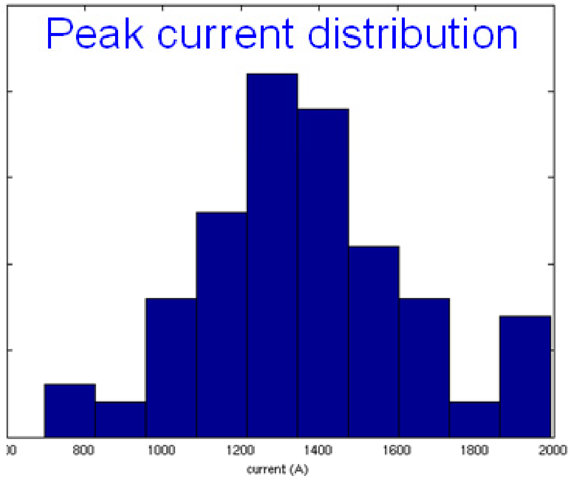
Gun Jitter Parameters (rms)

Solenoid Field	0.02e-3 T
Gun Phase	0.1 degrees
Gun Voltage	0.1%

Main linac cavities

Phase (P)	0.01 degrees
Bunch Comp. (B)	1e-5 fractional
Voltage (V)	1-e4 fractional





Arrival time jitter
70 fs FW

Peak current
mean 1.4 kA
std 270 A
20% rms fluctuation

A stable single spike operation requires more stringent tolerances

R. Bartolini et al., WEPC59

Conclusion and future work

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.

Seeded cascaded harmonic schemes produce signals with good temporal coherence and SASE FEL performance achieved exceeds 10^{11} ppp @ 1 keV

Jitter and tolerance analysis show that the required performance for the seeded cascaded harmonic scheme can be met

Alternative FEL operating mode under consideration: Single Spike operation is promising but has very serious jitter issues

Work is ongoing to improve the optimisation and to produce the Conceptual Design Report by the end of 2009

Acknowledgments

Thanks to the NLS Physics and Parameters working group:

C. Christou, J.H. Han, I. Martin, J. Rowland and R. Walker (DLS)

D. Angal-Kalinin, J. Clarke, D. Dunning, F. Jackson, B. Muratori, S. Smith, N. Thompson, P. Williams and M. Poole (ASTeC)

and

M. Venturini, A. Zholents (LBNL)

Acknowledgments

Thanks to the NLS Physics and Parameters working group:

C. Christou, J.H. Han, I. Martin, J. Rowland and R. Walker (DLS)

D. Angal-Kalinin, J. Clarke, D. Dunning, F. Jackson, B. Muratori, S. Smith, N. Thompson, P. Williams and M. Poole (ASTeC)

and

M. Venturini, A. Zholents (LBNL)

and

Thank you for your attention