
NLS compression scheme

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Outline

- Introduction

 - NLS project and users' requirements

- Optimisation of the 2.2 GeV Linac and AP challenges

 - layouts and performance

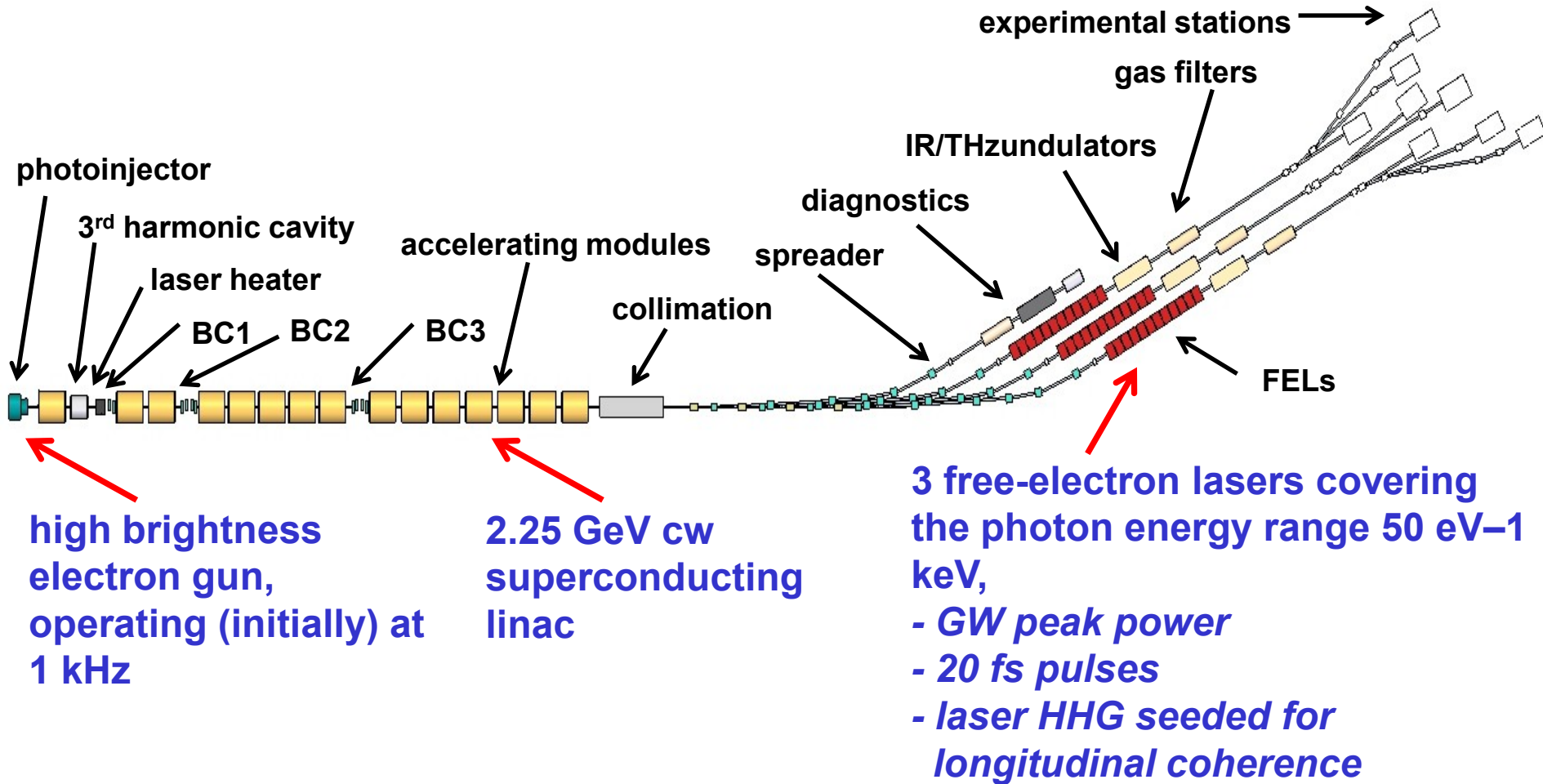
 - collective effects

 - control of the e^- phase space distribution

 - jitter issues

Conclusions

Layout of NLS



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

NLS main parameters



- 2.25 GeV
- 50-200 pC
- optimised L-band gun: 18 ps FW, 0.33 μm (proj. nor. emit.)
- LINAC L-band gradient ~ 20 MV/m \rightarrow also 15 MV/m
- 3HC @ 3.9 GHz ~ 15 MV/m
- Magnetic bunch compressors \rightarrow C-S-S-chicane compressors
- Beam spreader (modified LBNL type)
- Undulator train for a seeded cascaded harmonic generation scheme
- Compatibility with SASE operation for the generation of 20 fs pulses

Accelerator Physics challenges

Soft X-ray are driven by high brightness electron beam

1 – 3 GeV

$\varepsilon_n \leq 1 \mu\text{m}$

$\sim 1 \text{ kA}$

$\sigma_\gamma / \gamma \leq 10^{-4}$

This requires:

a low emittance gun (norm. emittance cannot be improved in the linac)

acceleration and compression through the linac keeping the low emittance

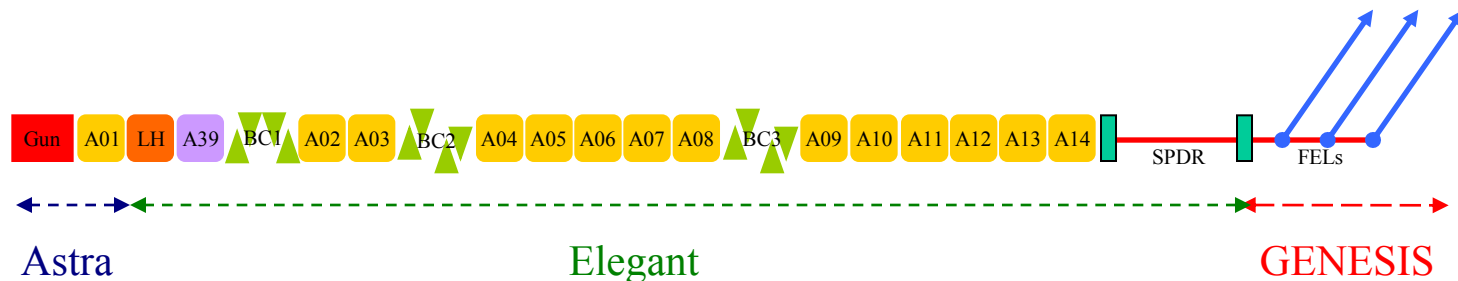
Requirements for the operation of seeded FELs

Assuming a 20 fs FWHM seed laser pulse we need an electron bunch with **constant slice parameters** over 20 fs plus the relative time jitter between the electron bunch and the laser seed pulse.

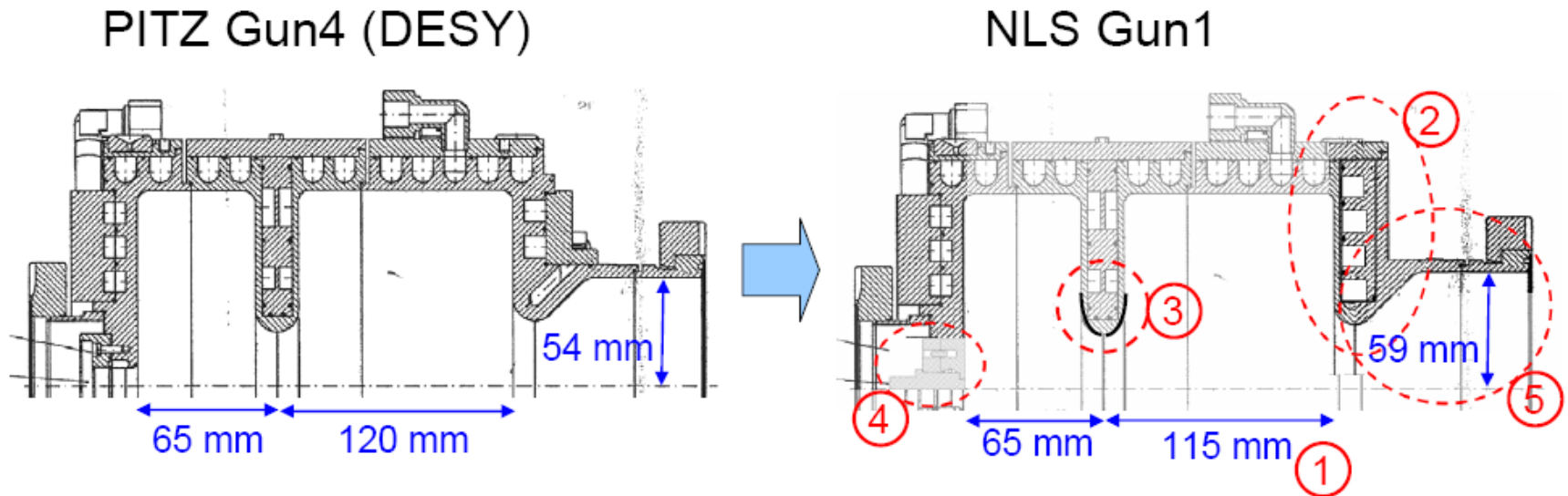
- constant slice parameters on a length of **100 fs – or longer**
- no residual energy chirp (or very limited)
- low sensitivity to jitter
- **The slice parameters to control are not only slice current, emittance, energy spread but also slice offset and angle and Twiss parameters**

Design and Optimisation of LINACs driving FELs

- Tracking studies to optimise the beam quality at the beginning of the undulators:
peak current, slice emittance, slice energy spread
- linac simulations include
CSR, longitudinal space charge, wake-fields in RF cavities
- Parameters used in the optimisation
Accelerating section and 3HC amplitude and phase,
Bunch compressors strengths (R_{56})
- Validation with full start-to-end simulation Gun to FEL (time dependent)**

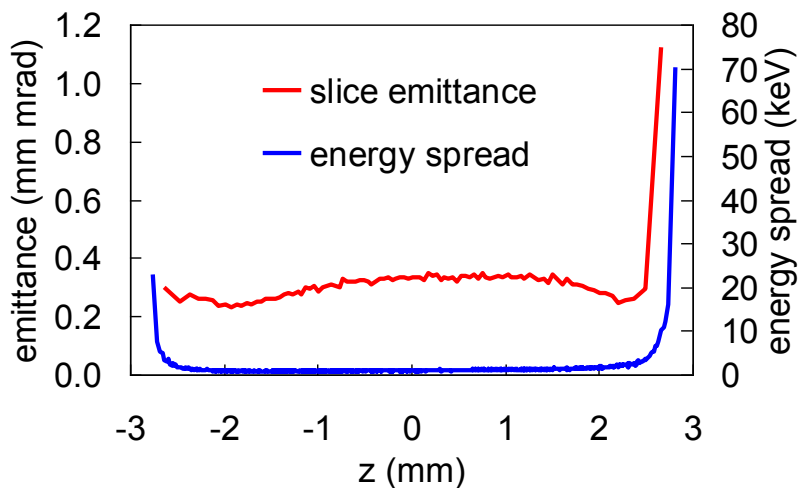
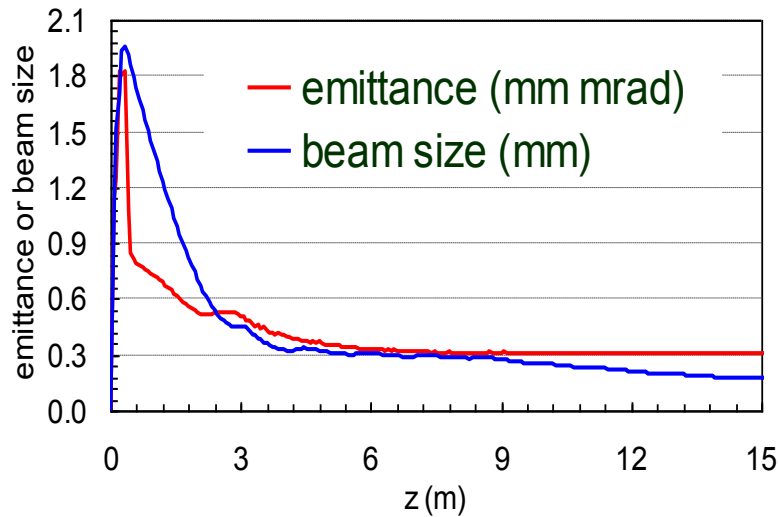


NLS L-band gun (modified Pitz type)

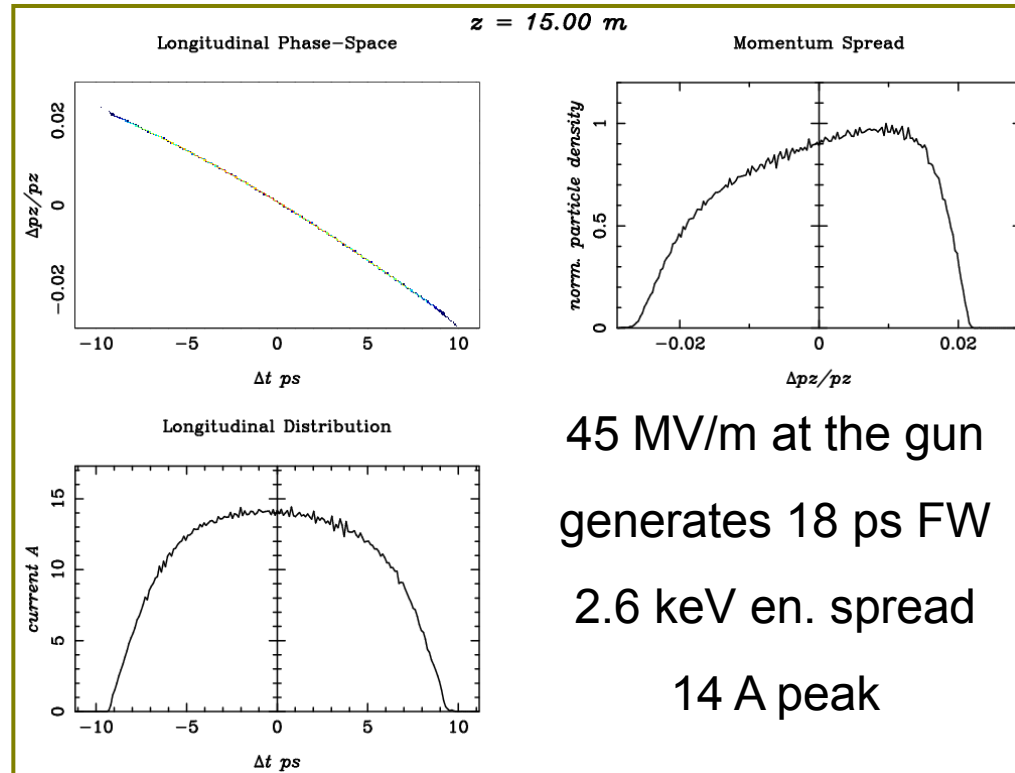


1. Cell lengths optimised for smaller emittance
2. Minor improvement of cooling-water channel
3. Iris shape to be elliptic for less surface field
4. Opening for cathode insertion improved for no scratch on the plug
5. Larger coupler radius for reducing wakefield

Injector optimisation for 200 pC



longitudinal phase space

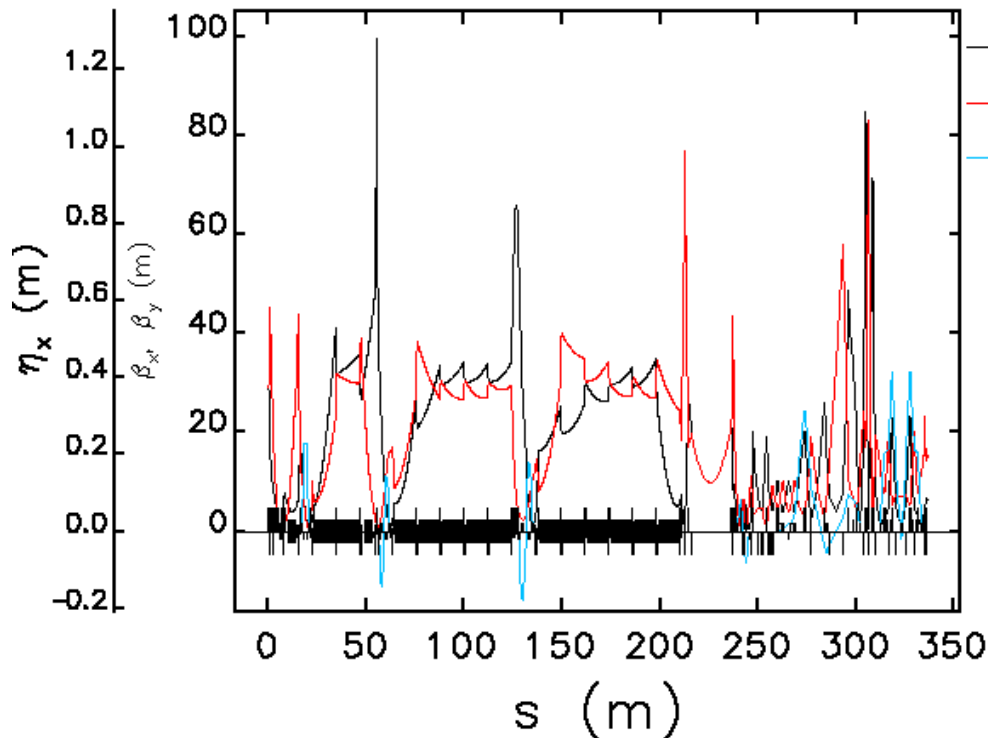


45 MV/m at the gun
generates 18 ps FW
2.6 keV en. spread
14 A peak

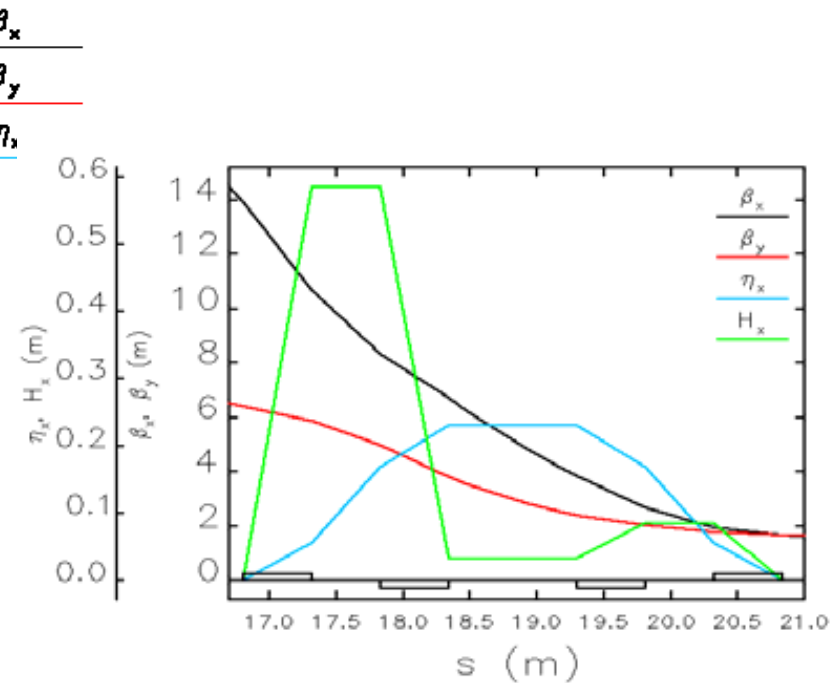
core emittance: 0.304 (100%)
(mm mrad) 0.227 (95%)

Courtesy J.H. Han

Linac optics functions



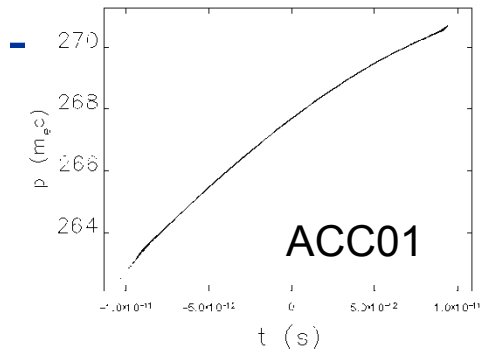
Twiss parameters for nsl_0p2nC_schic



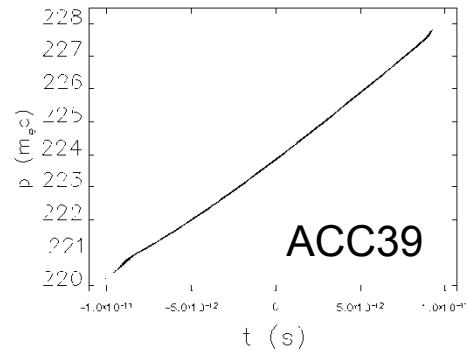
One C-chicane and two S chicanes with 4 dipoles; minimum β_x at dipole 4

Spreader based on LBNL TBA design added sextupoles to control CSR

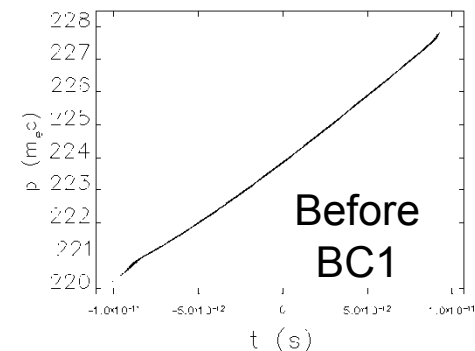
Beam evolution along the linac: 2M particle tracking



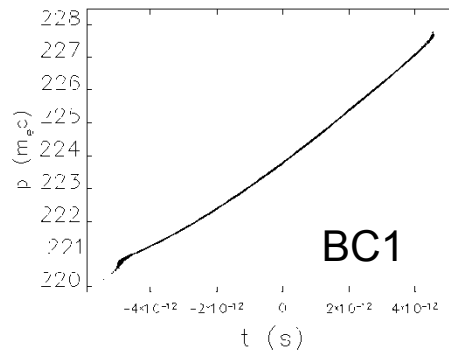
watch-point phase space --input: nsl_dp2nc_schic.ele lattice: nsl_dp2nc_schic.lite



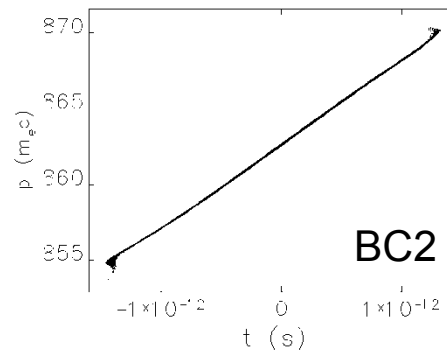
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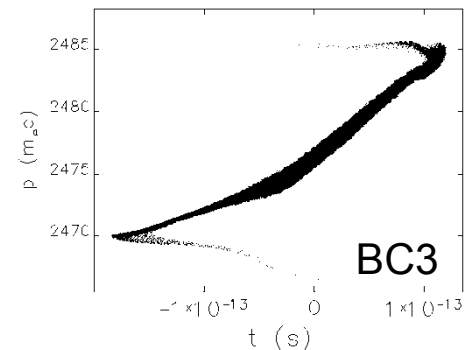
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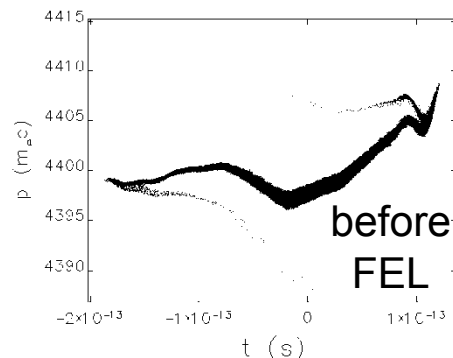
watch-point phase space --input: nsl_dp2nc_schic.ele lattice: nsl_dp2nc_schic.lite



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watch-point phase space --input: nsl_dp2nc_schic.ele lattice: nsl_dp2nc_schic.lite



watch-point phase space --input: nsl_dp2nc_schic.ele lattice: nsl_dp2nc_schic.lite

18 ps FW at start

9 ps FW at 115 MeV

3 ps FW at 440 MeV

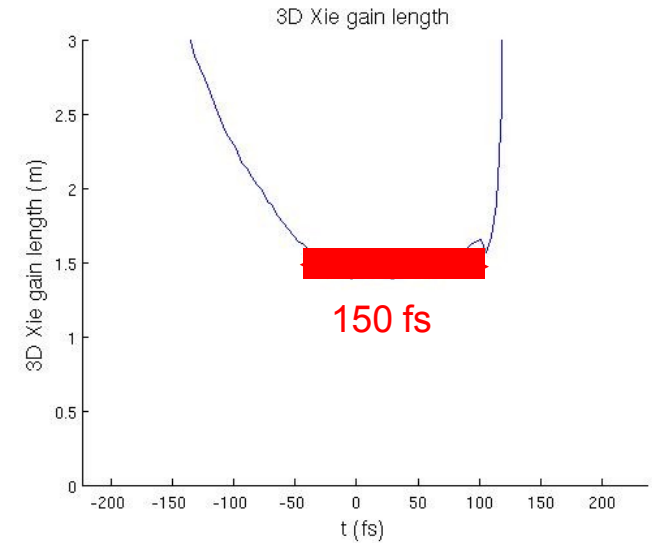
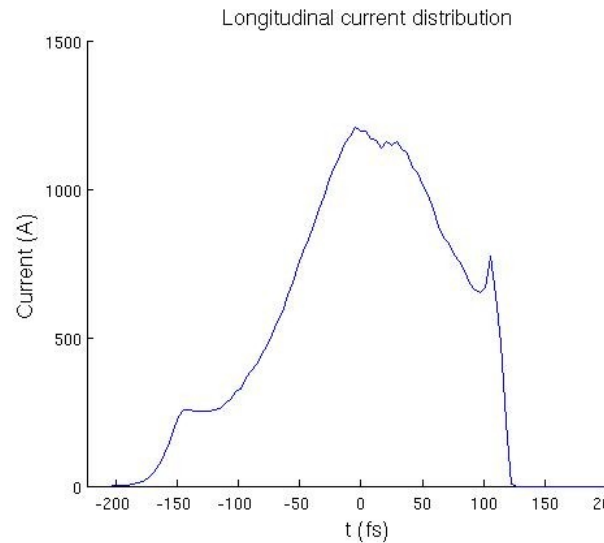
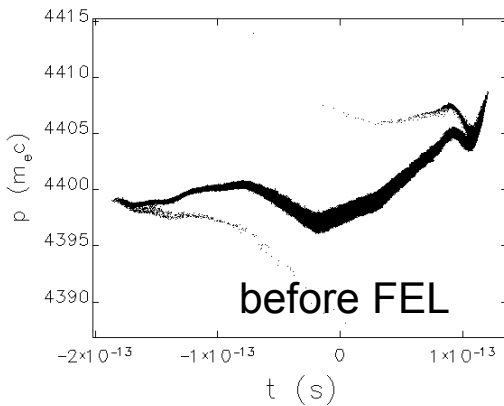
250 fs FW at 1.26 GeV

compression ratio 2

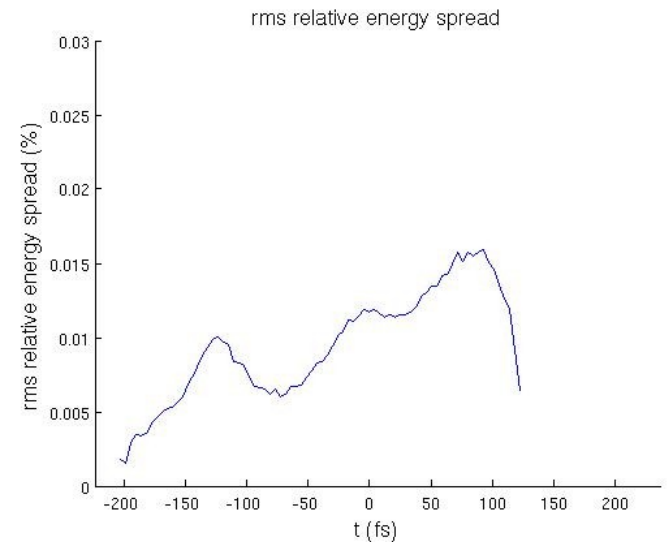
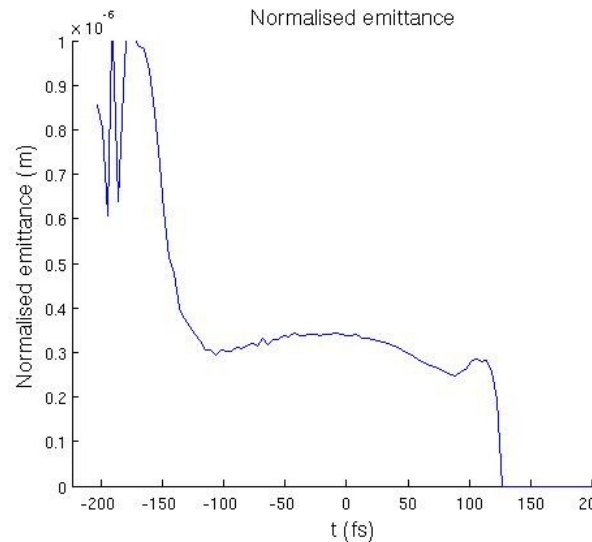
compression ratio 3

compression ratio 12

Slice analysis of electron beam at the FEL



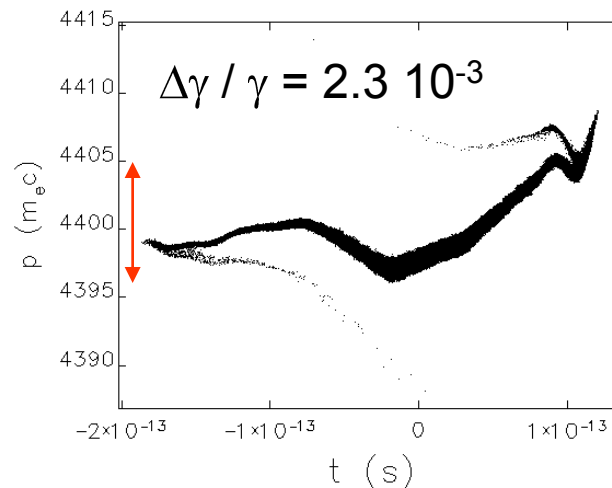
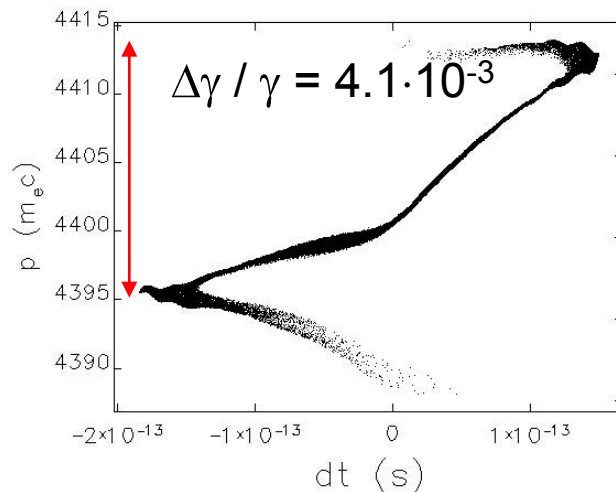
BC1	-82.5 mm
BC2	-112 mm
BC3	-104 mm
Ph 2-3	10°
Ph 4-8	5°
Ph 3HC	181°
V RF	20 MV/m
V 3HC	8.1 MV/m



Energy chirp issue

Time dependent simulations in the seeded harmonic cascade schemes showed that 0.02 MeV/fs is an acceptable energy chirp. This corresponds to a $\Delta\gamma/\gamma \sim 2 \cdot 10^{-4}$ over a 20 fs seed. 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

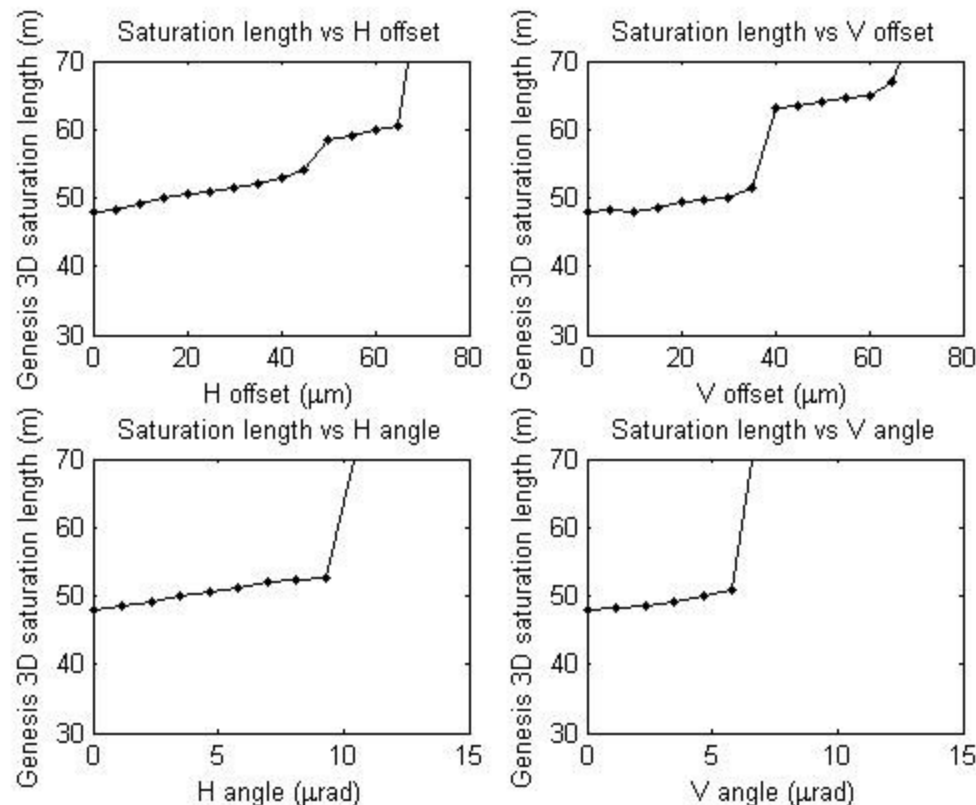


S-Chicanes vs C-Chicanes: slice angle and offset (I)

Saturation length depends on slice H offset, V offset, H angle, V angle

ideal undulator train; genesis SS simulations

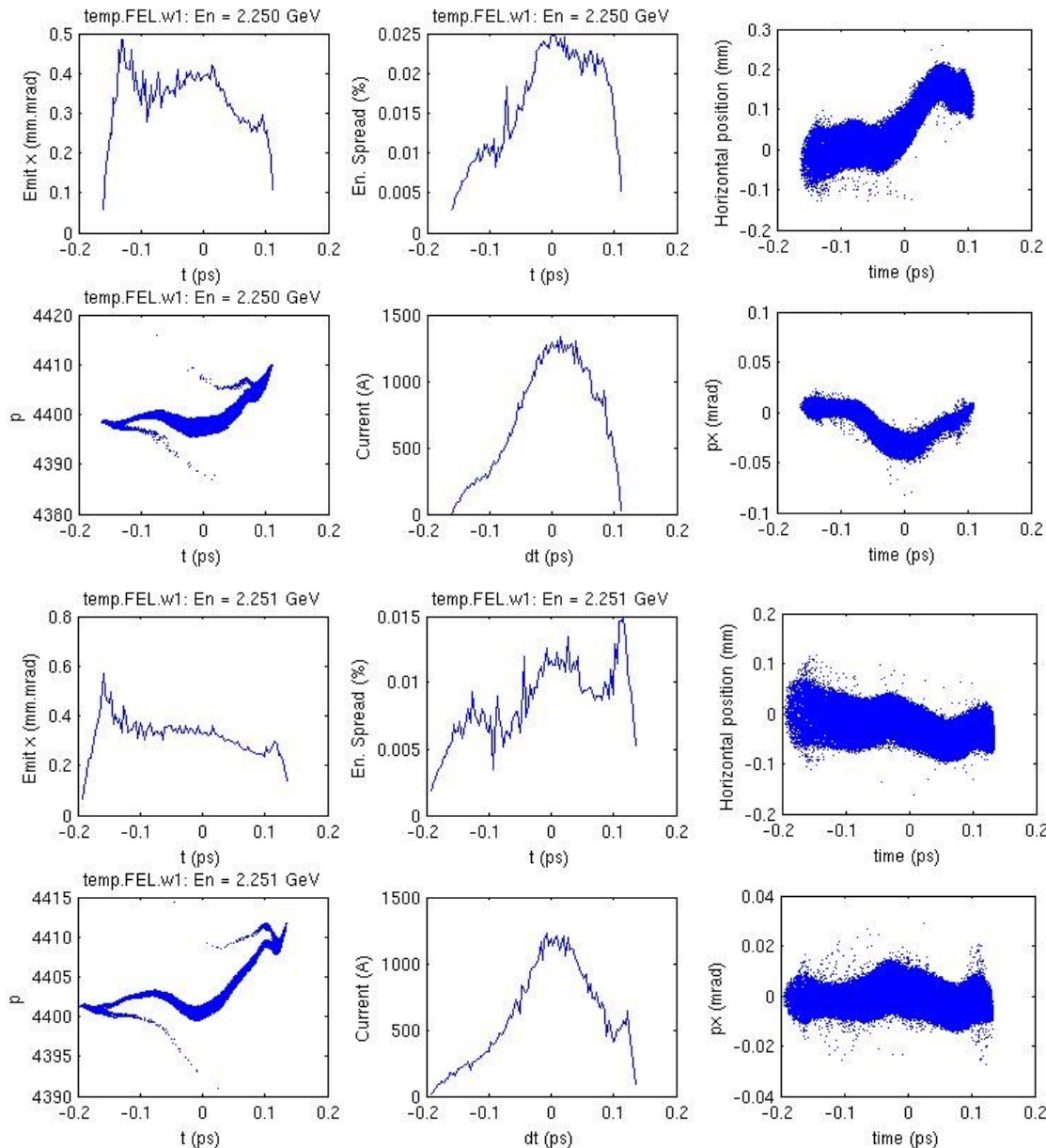
(normalis. emitt. $\varepsilon_x = 0.4 \mu\text{m}$, relative energy spread $2\text{e-}4$, $I_{\text{peak}} = 1.2 \text{ kA}$)



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)



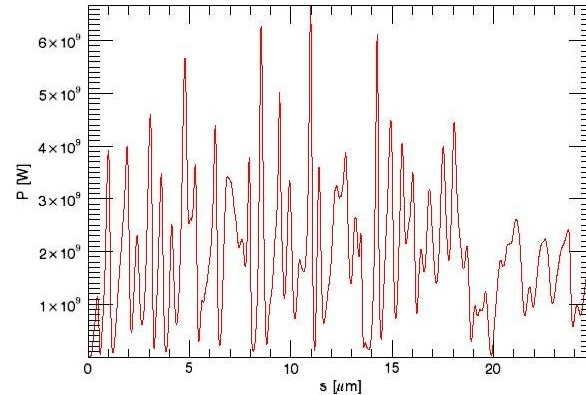
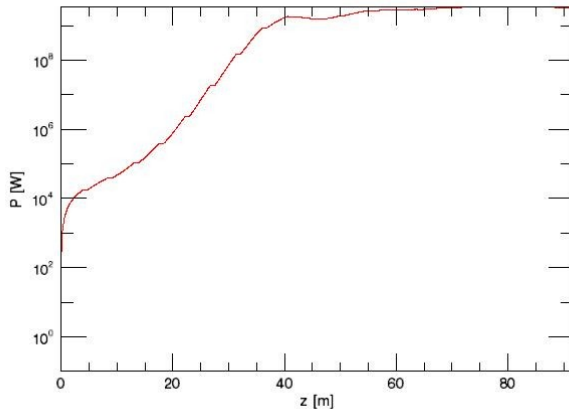
The angle and offset in the slices with the C-type chicanes is

almost $200 \mu\text{m}$ and $50 \mu\text{rad}$

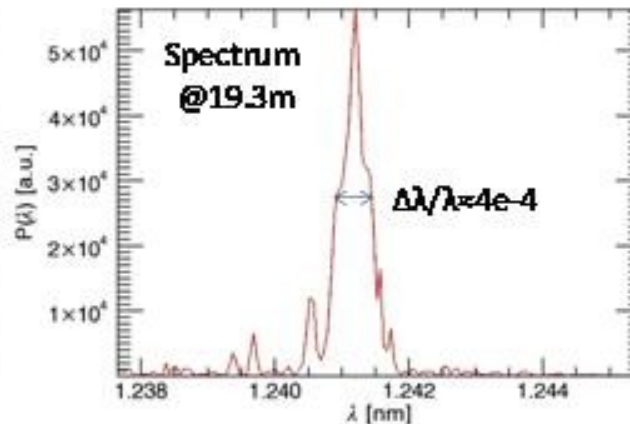
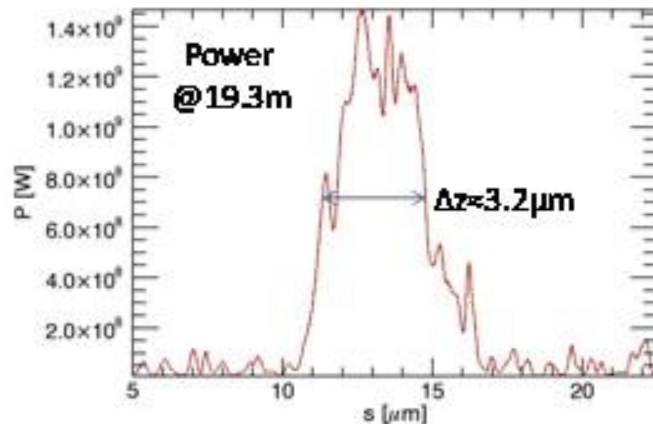
With S-type chicanes this is significantly corrected while keeping a good slice emittance, slice energy spread and peak current

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

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

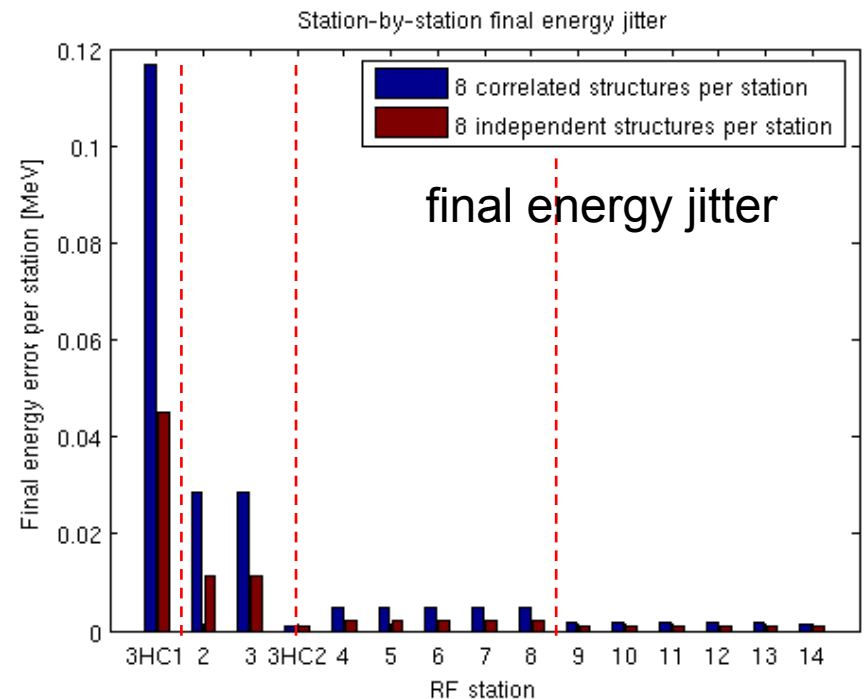
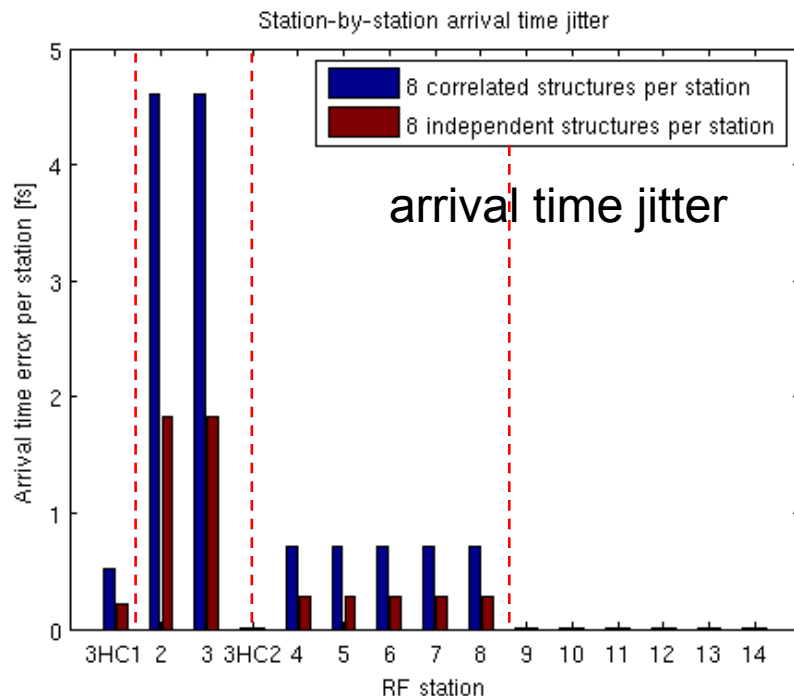
Amplitude and phase jitter applied to each cavity in the linac one by one.

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)
Voltage (V)

0.01 degrees
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

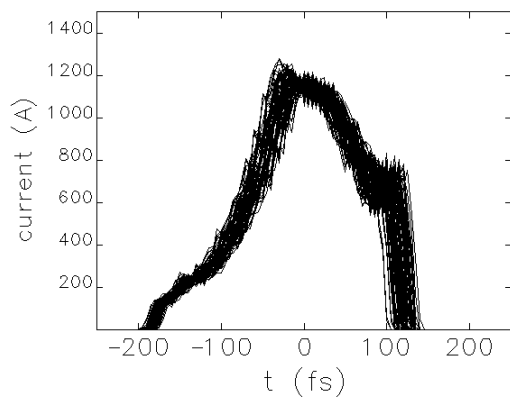
Main linac cavities

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

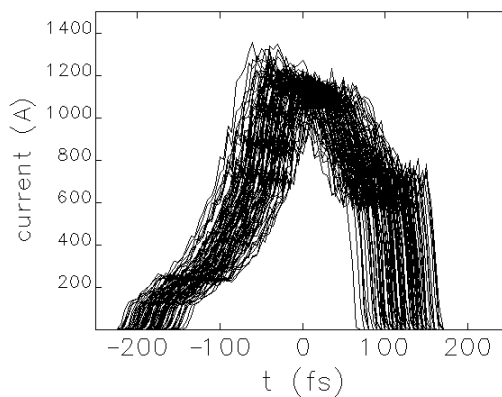
RF gun (P and V)	7 fs
Injector (RF gun + ACC01)	21 fs
Main linac RF P	3 fs
Main linac RF V	9 fs
BCs power supplies	20 fs
P + V + B combined	20 fs
P + V + B + I combined	30 fs

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

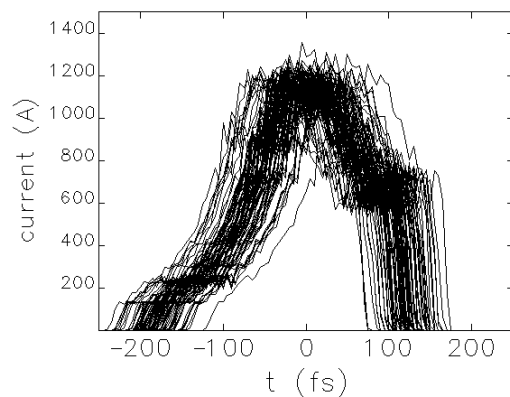
Longitudinal current profile jitter



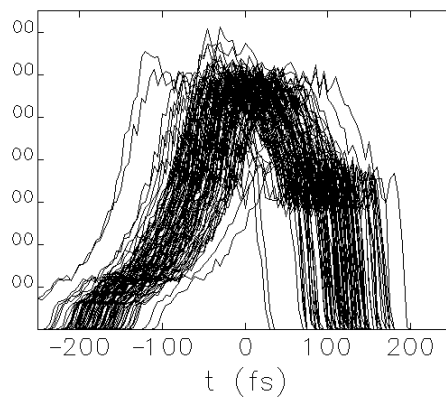
RF gun; 7 fs rms



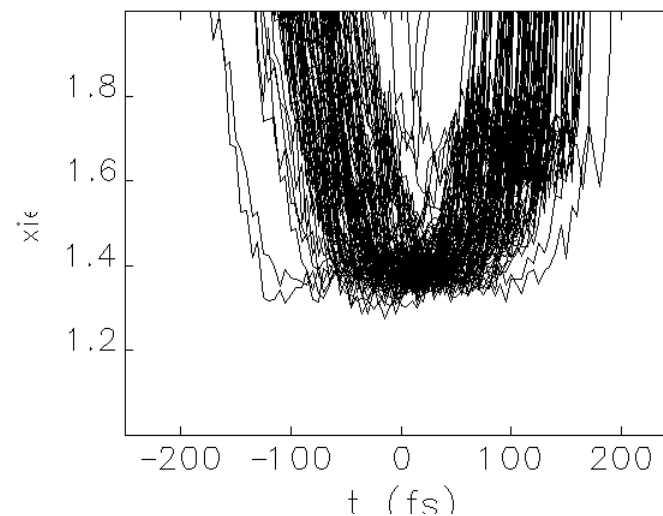
RF gun + ACC01;
21 fs rms



all linac wo injector;
20 fs rms



all linac: 30 fs rms



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

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)

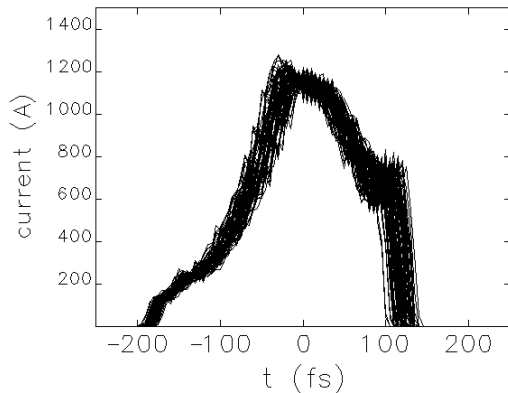
Solenoid Field 0.02e-3 T
 Gun Phase 0.1 degrees
 Gun Voltage 0.1%
 Charge 1%
 X Offset 0.025 mm

Main linac cavities **with split ACC01**

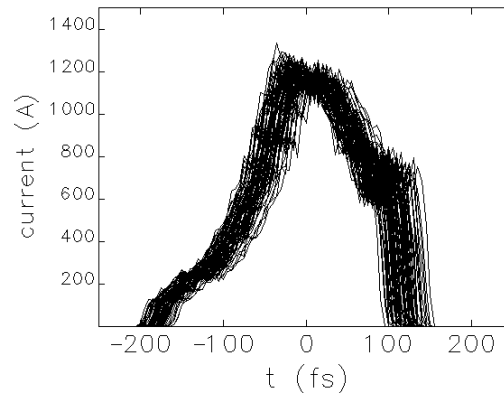
Phase (P) 0.01 degrees
 Bunch Comp. (B) **1e-5 fractional**
 Voltage (V) 1-e4 fractional

	arrival time		mean energy variation
RF gun (P and V)	7 fs	7 fs	0.005%
Injector (RF gun + ACC01)	21 fs	11 fs	0.005%
Main linac RF P	3 fs	3 fs	0.002%
Main linac RF V	9 fs	9 fs	0.001%
BCs power supplies	20 fs	4 fs	<0.001%
P + V + B combined	20 fs	10 fs	0.003%
P + V + B + I combined	30 fs	14 fs	0.006%

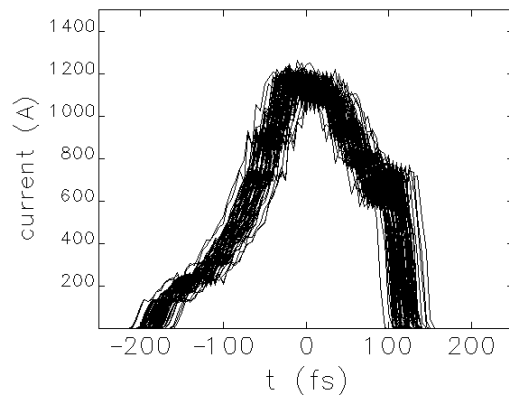
Electron beam jitter sources and results



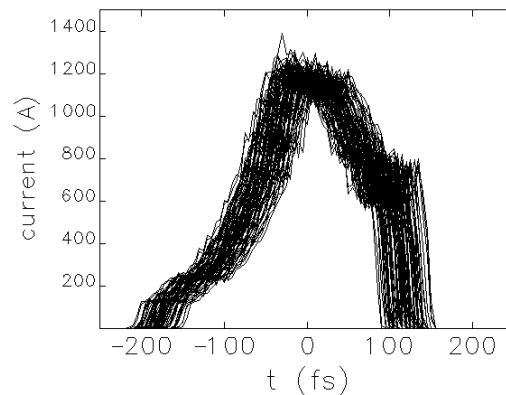
RF gun: 7 fs rms



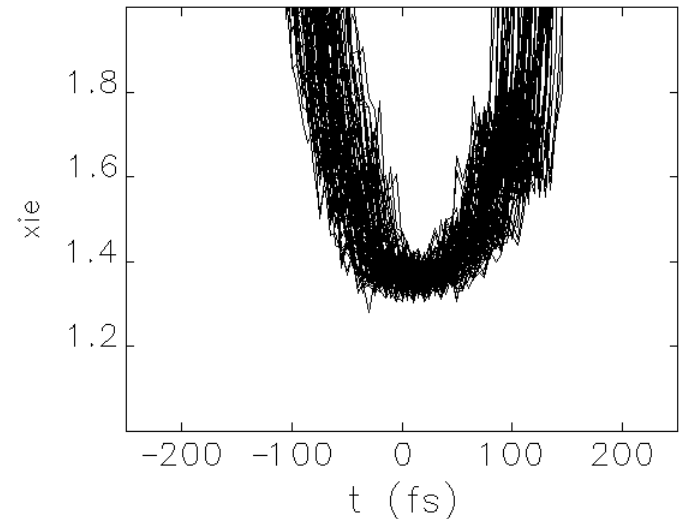
RF gun + ACC01:
11 fs rms



linac wo injector:
10 fs rms

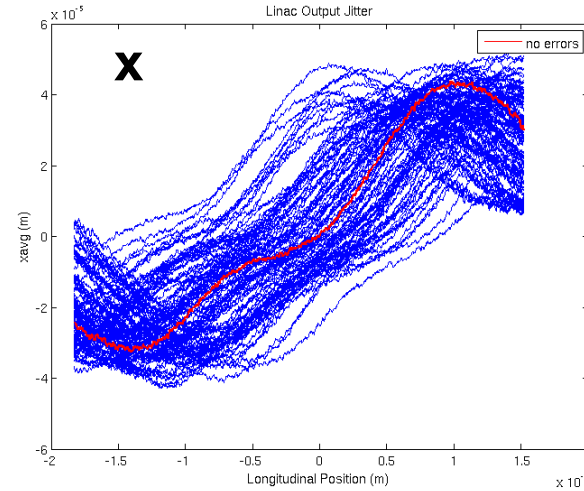
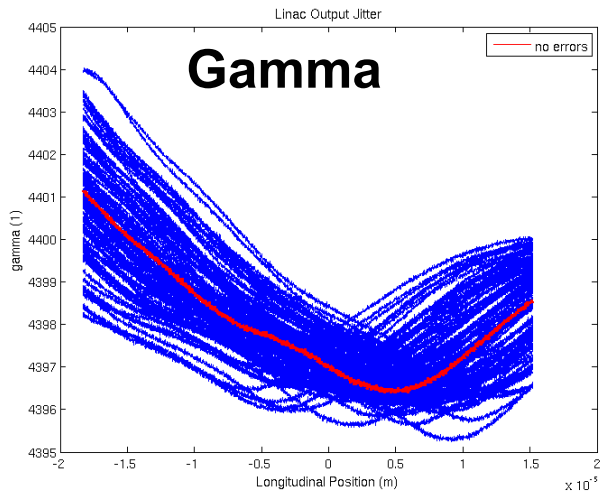
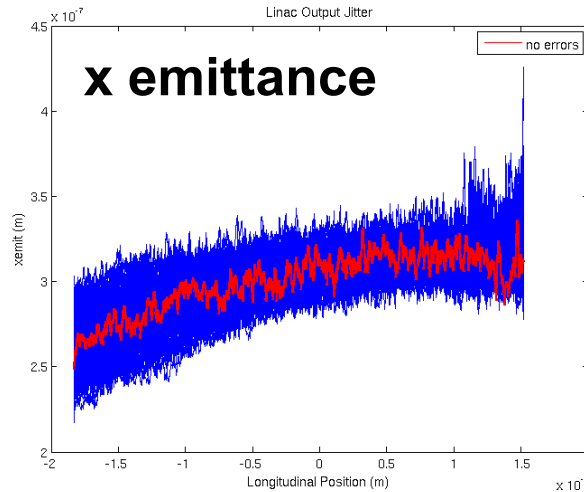
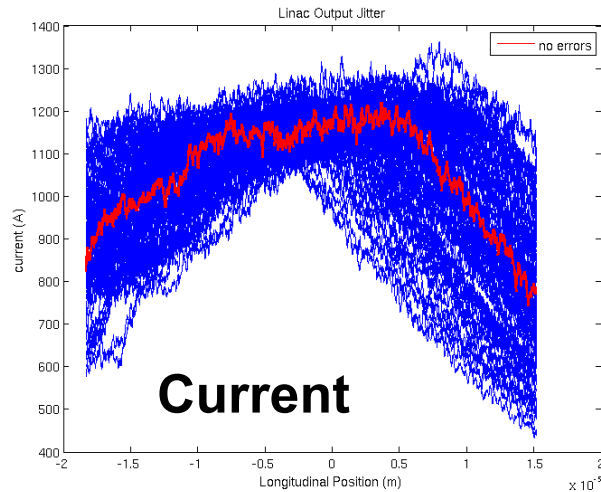


all linac: 14 fs rms

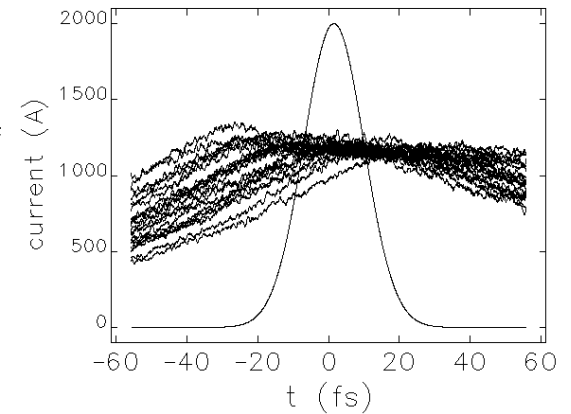


The 3D Xie length computed for each slice has a flat area that can accommodate the 20 fs seed laser pulse

100 bunches with jitter at beginning of the modulator

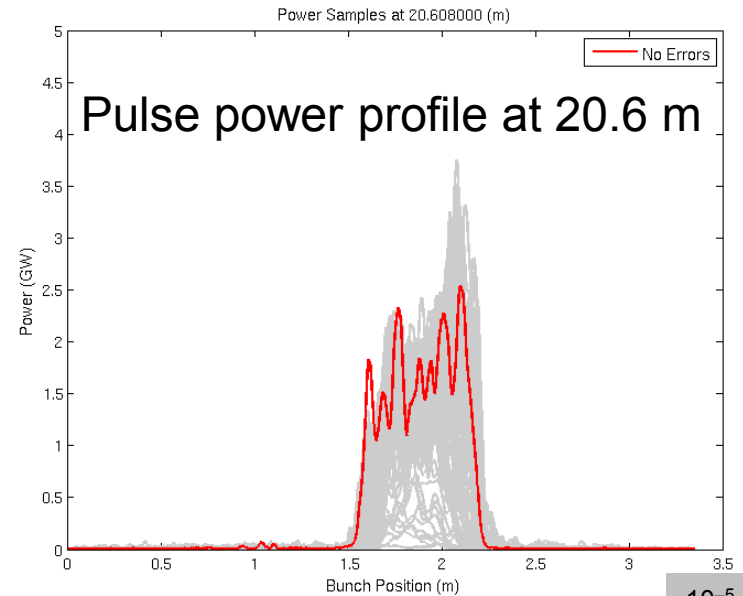
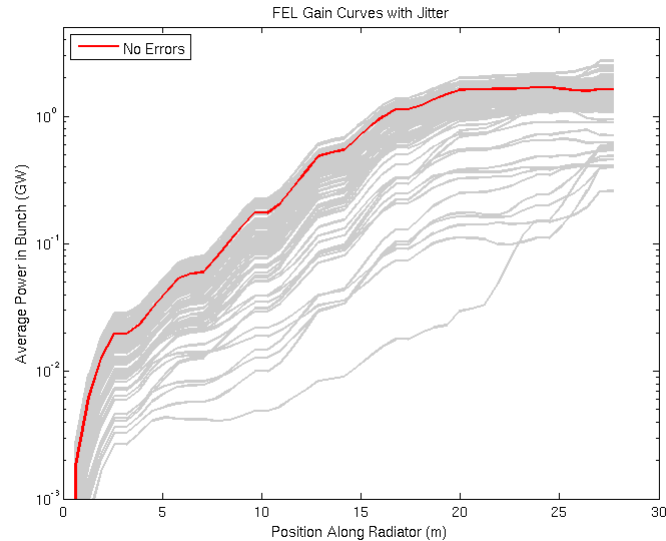


1M particles
bunches



Seed location

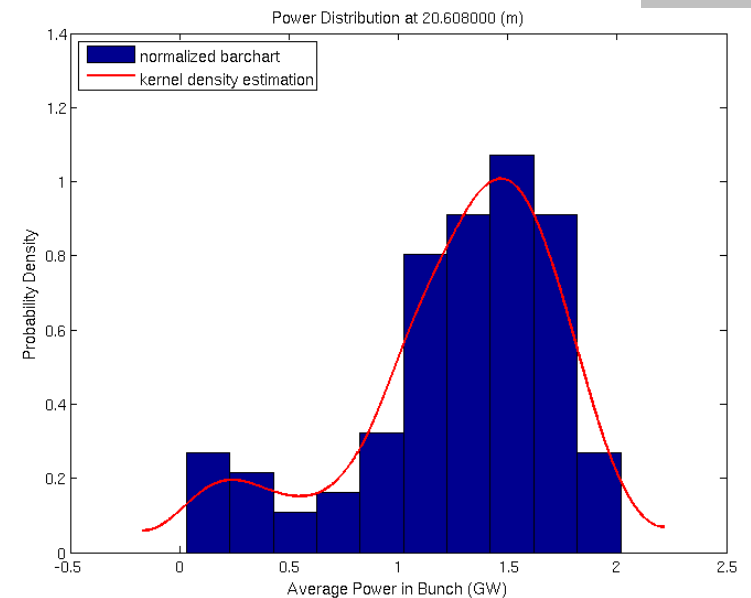
FEL Radiation Jitter (FEL3 – 1keV)



10^{-5}

FEL3 at 1 keV cascade scheme
(Zhirong's revision – see N.Thompson's talk)
100 electron bunches with jitter sent to the FEL

Average power at 20.6 m = 1.4 GW
rms of power = 0.3 GW



Microbunching instability mitigation: machine design

Choices of number of compressors, compression ratio and compression energy may impact the overall effect of microbunching instability. Solutions adopted are machine dependent

	number of BCs	Compressor type	Compression Energies (MeV)	Compression factors	pulse length FWHM (ps)	peak current (A)
Wi-FEL	1 BCs	C	400	20	3 to 0.16	50 to 1000
FERMI	2 BCs	C-C	220-600	$3.5 \times 3 = 10.5$	10 to 0.95	1000
SPARX	3 BCs	C(VB)-C-S	300-500-1500	70	6 to 0.08	35 to 2500
LBNL	1 BC	C	250	14	0.6	1200
FLASH	2 BCs	C-S	130-470	~ 100	12 to 0.1	12 to 1200
NLS	3 BCs	C-S-S	130-450-1400	$2 \times 3 \times 12 = 72$	20 to 0.25	15 to 1100

XFEL	2 BCs	C-C	400-2000	$20 \times 5 = 100$	15 to 0.15	50 to 5000
Swiss XFEL	2 BCs	C-C	400-2000	$12 \times 6 = 72$	12 to 0.16	20 to 1600
LCSL	2 BCs	C-C	250-4300	$7.5 \times 12 = 90$	2 to 0.25	33 to 3000
Spring 8	3 BCs	C-C-C	30-410-1400	$7 \times 10 \times 6 = 420$	~ 40 to 0.1	10 to 4000

1, 2 or 3 BCs?

Initial conditions can be different

- say for 200 pC

- L-band (45-50 MV/m) generate longer e- pulses (12-15 ps FWHM)

- S-band (100-120 MV/m) generate (6- 8 ps FWHM)

- .blow out regime – Thermionic gun are even more different

Applications requirements can also be different

- SASE

- Seeded with different requirements on the pulse length

- fresh bunch technique

- single spike

Experience with NLS show that 3 BCs is adequate for seeded harmonic cascades and single spike operation with an L-band gun based injector

Microbunching is well controlled (gain is small < 10 - M. Venturini)

Laminar parameter for NLS

Comparison for space charge regime Ferrario et al. NJP 8, 295, (2006)

$$\sigma + \frac{\gamma}{\gamma} \sigma + \frac{1}{\gamma} \sigma = \frac{k_s}{\gamma} \sigma + \frac{\varepsilon_h}{\gamma^2} \sigma$$

$$\rho = \left(\frac{k_s}{\varepsilon_h \gamma \sqrt{1/4 + \gamma^2}} \right) <$$

$$\varepsilon_{nx} = 0.4 \mu\text{m}$$

$$E_{\text{acc}} = 20 \text{ MV/m}$$

18 ps FW at start

9 ps FW at 115 MeV

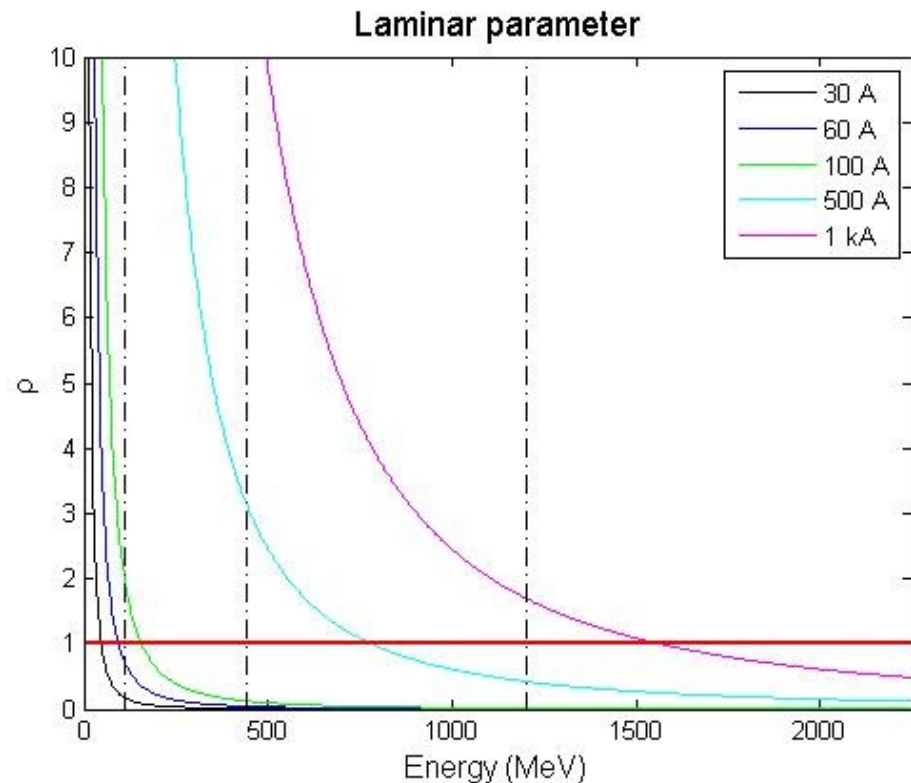
3 ps FW at 440 MeV

250 fs FW at 1.26 GeV

compression ratio 2 at BC1 (15A → 30 A)

compression ratio 3 at BC2 (30A → 90 A)

compression ratio 12 at BC2 (90A → 1.1 kA)



Conclusions and ongoing work

NLS' CDR is going to be finished in May 2010 despite the project has been “postponed”

The operating gradient has been reduced to 15 MV/m but no significant impact on the compression scheme has been found

BC3 has been moved to higher energy (1.4 GeV) to operate with a laminar parameter below one

Thank you for your attention