Single spike FEL pulses with a chirped electron beam

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on behalf of the SPARC team

outline

- Interest on chirped electron beams for FEL production
- SPARC
  - diagnostic
  - Velocity bunching
    - transverse phase space
    - longitudinal phase space
  - FEL beamline
- FEL light with a chirped beam
- chirp compensation with tapering
- Harmonics
- preliminary FROG measurements
- conclusions

Chirped electron beams for FELs

A method to enhance specific FEL pulse properties (time, peak power,…)

We know that:

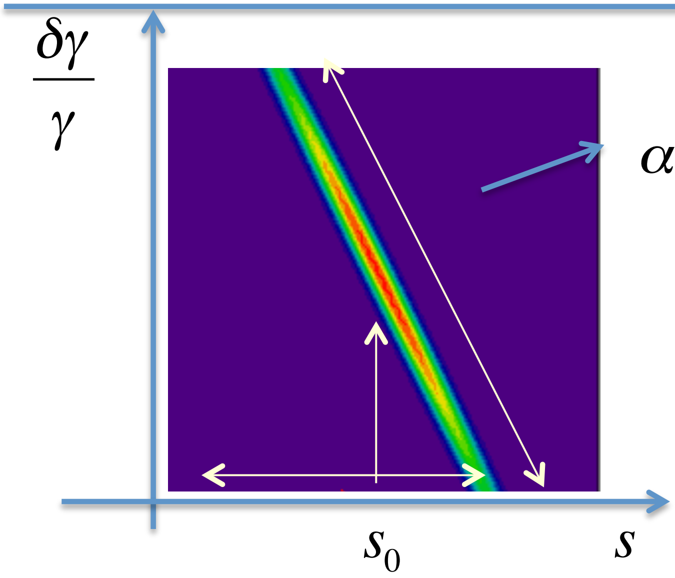
- the chirp on the electron bunch is transferred to the light pulse;

$$\left(\frac{\delta\omega}{\omega} \approx 2\frac{\delta\gamma}{\gamma}\right)$$

- the overall pulse spectral width is function of the chirp;
- The FEL performances preserved by the use of undulator tapering;
  (Saldin, Schneidmiller, Yurkov, PRSTAB 9, 2006)

Chirped electron beams for FELs

[1] C.Pellegrini, NIM A 445 (2000), 124-127
[2] S.Krinsky and Z.Huang, PRSTAB Vol. 6, 2003
[3] C.B. Schroeder et al., NIM A 483 2002, 89-93
[4] Saldin, Schneidmiller, Yurkov, PRSTAB 9, 2006
[5]L. Giannessi et al. PRL 106,144801, 2011



$$\alpha = \frac{1}{\gamma}\frac{\partial\gamma}{\partial s} \xrightarrow{\alpha = \frac{1}{L_b}\frac{\Delta\gamma}{\gamma}} \gamma(s) = \gamma(s_0)(1+\alpha(s-s_0))$$

$$\frac{\partial\omega}{\omega} \approx 2\frac{\partial\gamma}{\gamma} = 2\alpha\Delta s = \sqrt{\frac{\rho\lambda_u}{z(s)}}$$

$$\delta s_c = \frac{1}{2\alpha}\sqrt{\frac{\rho\lambda_u}{z(s)}} \xrightarrow{@\ saturation} \frac{\rho}{2\alpha} \approx \frac{\rho}{2\frac{\Delta\gamma}{\gamma}}L_b$$

$$\lambda_{coh}\cdot N_s = L_b \le \delta s_c$$

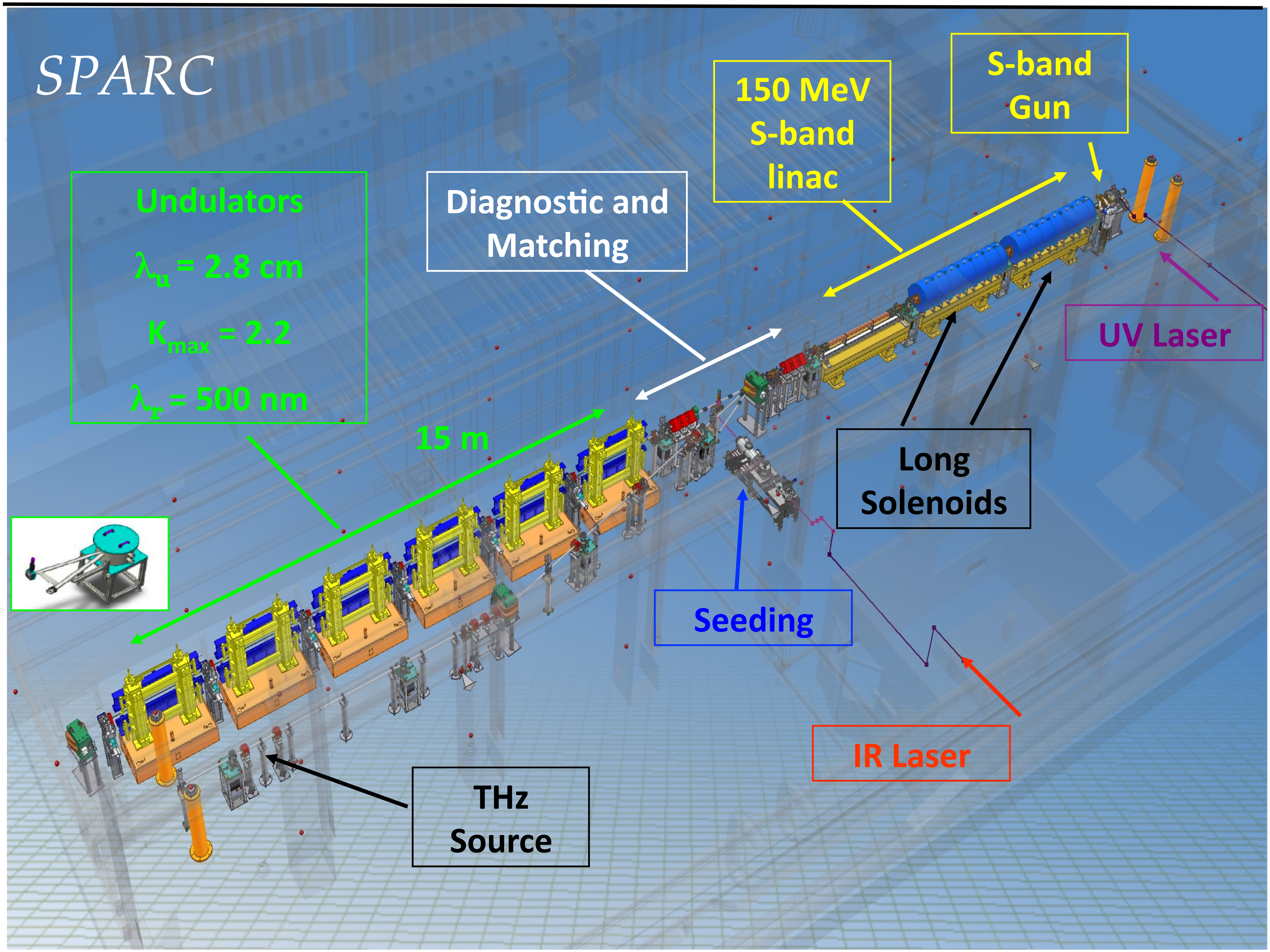
- FEL BW=ρ

$$L_b \ge \delta s_c, \lambda_{coh} \le \delta s_c$$

- FEL BW dominated by the chirp
- multiple single spike behaviour
- still high gain in the single spike

Pulse compression [1]
Monochromator for pulse duration control [2]
use to seed a second undulator [3]
Short bunch production by the use of und. tapering for selective gain suppression [4]
Single spike production with high charge beams [5]

SPARC



S-band Gun

150 MeV S-band linac

Diagnostic and Matching

Undulators

$\lambda_u = 2.8$ cm

$K_{max} = 2.2$

$\lambda_r = 500$ nm

15 m

UV Laser

Long Solenoids

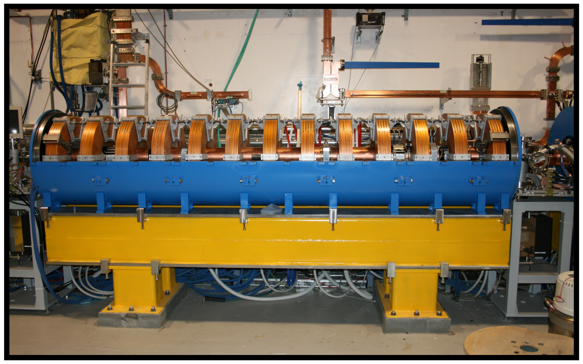
Seeding

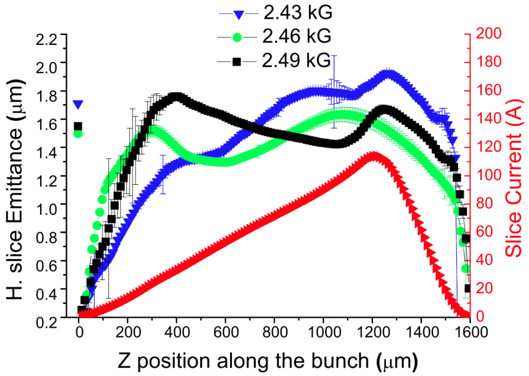
IR Laser

THz Source

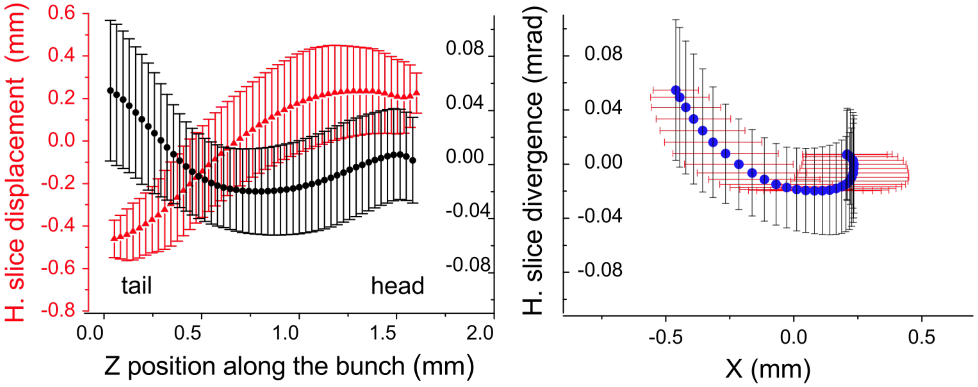
Velocity bunching: transverse phase space

- Slice emittance preserved by continous focusing along the linac (invariant envelope)

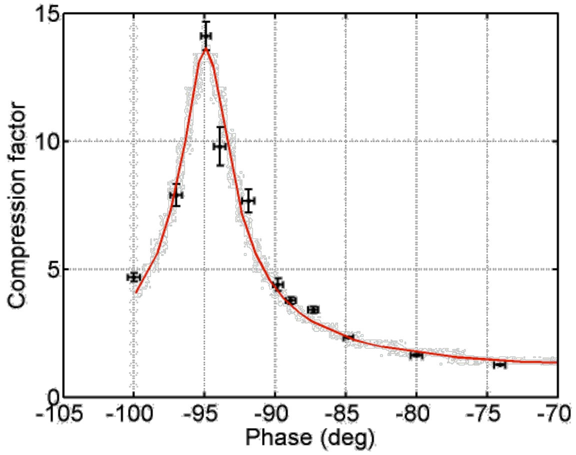


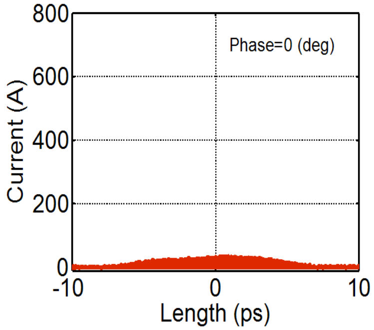


•Transverse/longitudinal correlations created in the process can be minimized optimizing the trajectory



Velocity bunching: longitudinal phase space



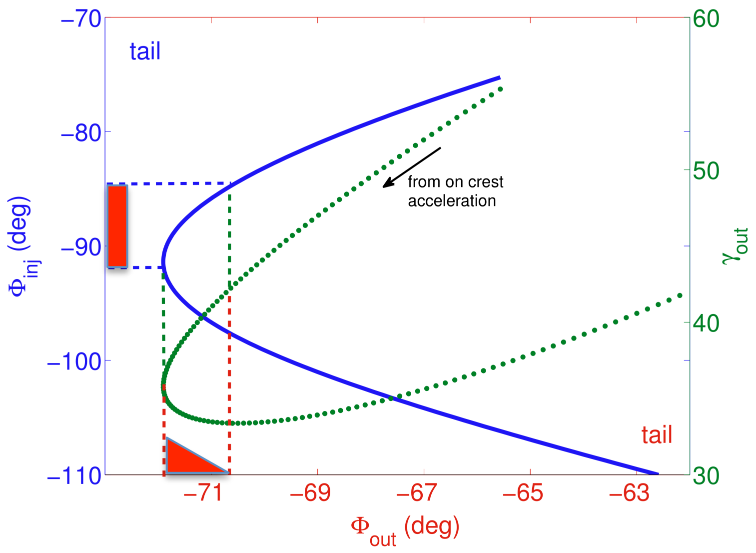


example for compression C=3

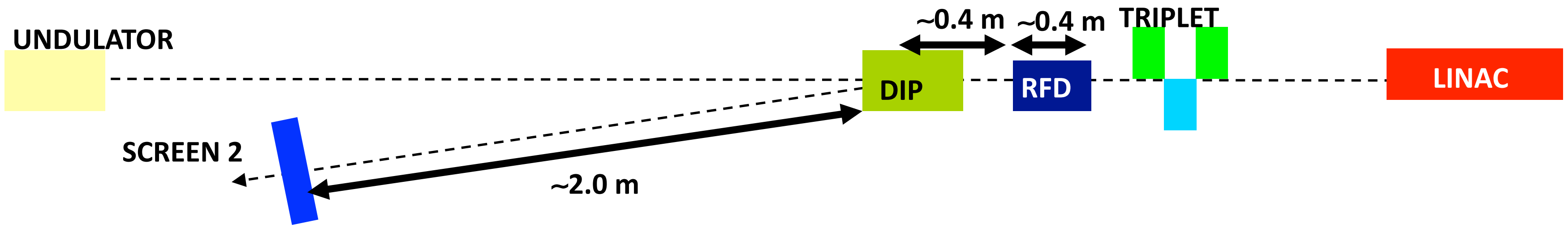
	No compression	Compression @C3
Bunch charge	280 pC	280pC
Injection phase (S1)	0 deg (on crest)	-87deg
Beam Energy	147.5 MeV	**101 MeV**
Total energy spread	0.11%	**1.1%**
Bunch length	3.01ps RMS	0.97ps RMS
TW Solenoid field	0	**450 Gauss (45 Amps)**

$$\frac{\partial \gamma}{\partial z} = -\frac{eE_0}{mc^2}\sin\phi$$

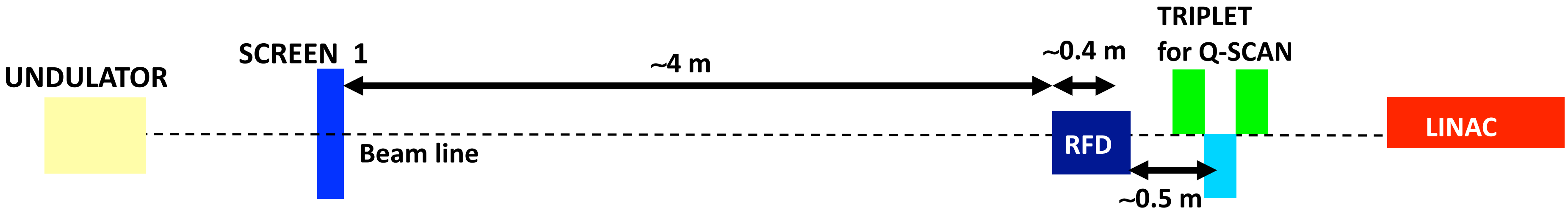
$$\frac{\partial \phi}{\partial z} = k\left(1 - \frac{\gamma}{\sqrt{\gamma^2 - 1}}\right) \quad \longleftrightarrow \quad \delta\beta \approx \frac{\delta\gamma}{\beta\gamma^3}$$

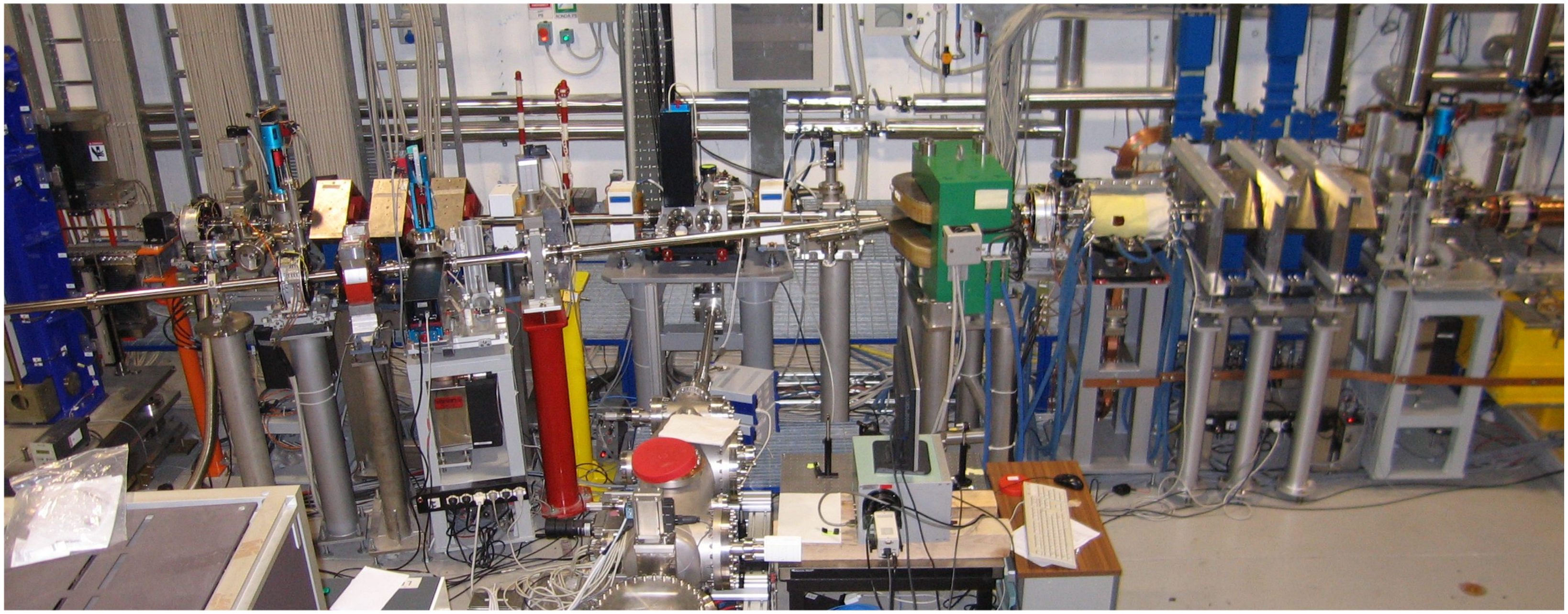


General measurement setup: longitudinal phase space



General meas. setup: beam profile and transverse slice emittance





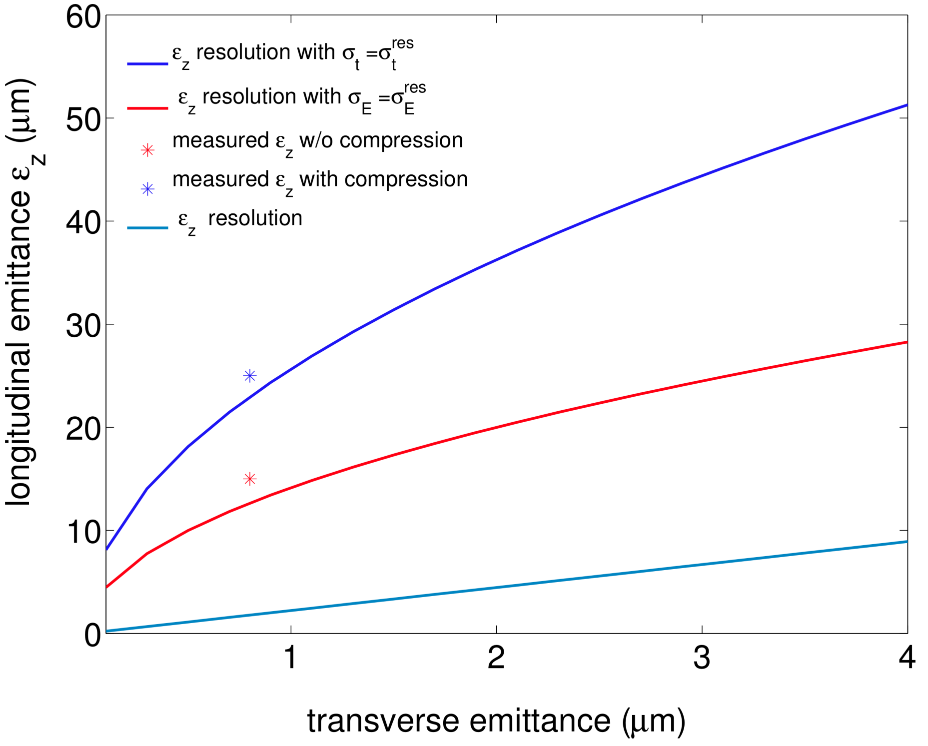
Longitudinal phase space measurements

P-W theorem and electron beam transverse emittance limit the intrinsic cavity resolution

$$\left(\frac{\sigma_E^{ind}}{m_0c^2}\right)\cdot\left(c\sigma_\tau^{ris}\right)=\sigma_y\sigma_y^{'}$$

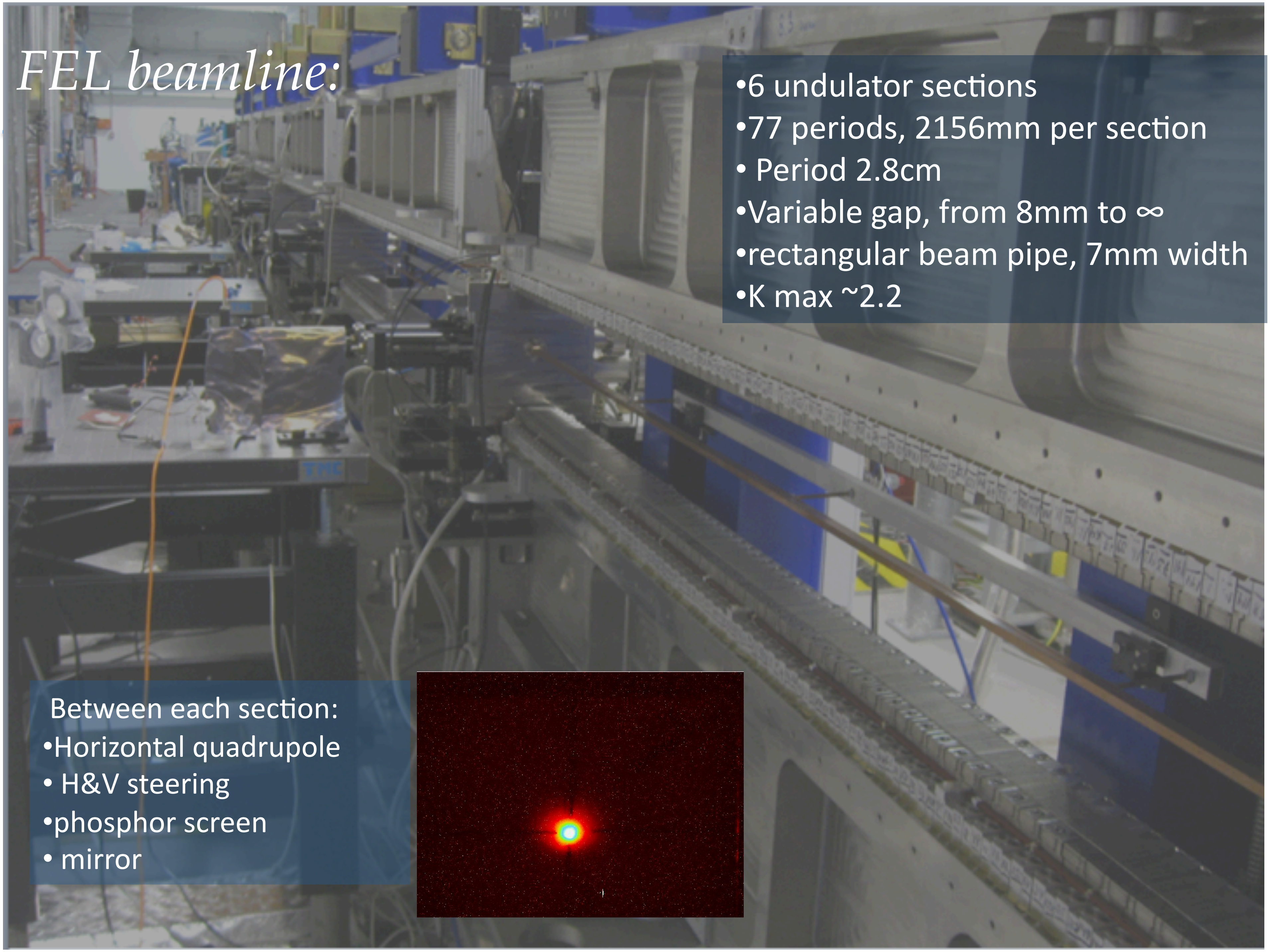
in case of drift:

$$\left(\frac{\sigma_E^{ind}}{m_0c^2}\right)\cdot\left(c\sigma_\tau^{ris}\right)=\varepsilon_y^n\sqrt{1+\frac{L^2}{(\beta_y^*)^2}}$$



Reliable measurements of bunch length, slice emittance, long. phase space correlations.
Limited in the measure of absolute value of longitudinal emittance, and slice energy spread

FEL beamline:

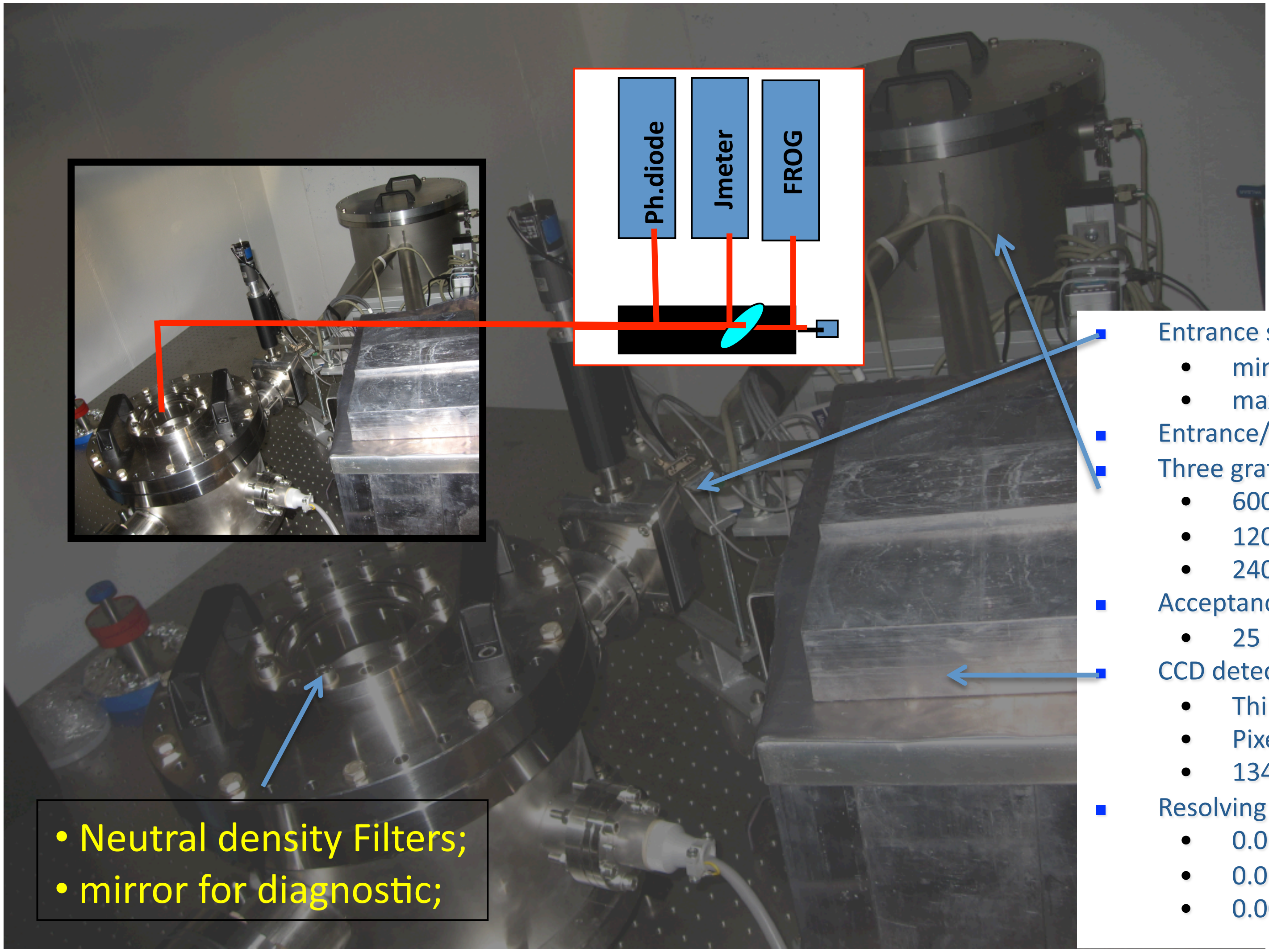


- 6 undulator sections
- 77 periods, 2156mm per section
- Period 2.8cm
- Variable gap, from 8mm to ∞
- rectangular beam pipe, 7mm width
- K max ~2.2

Between each section:

- Horizontal quadrupole
- H&V steering
- phosphor screen
- mirror

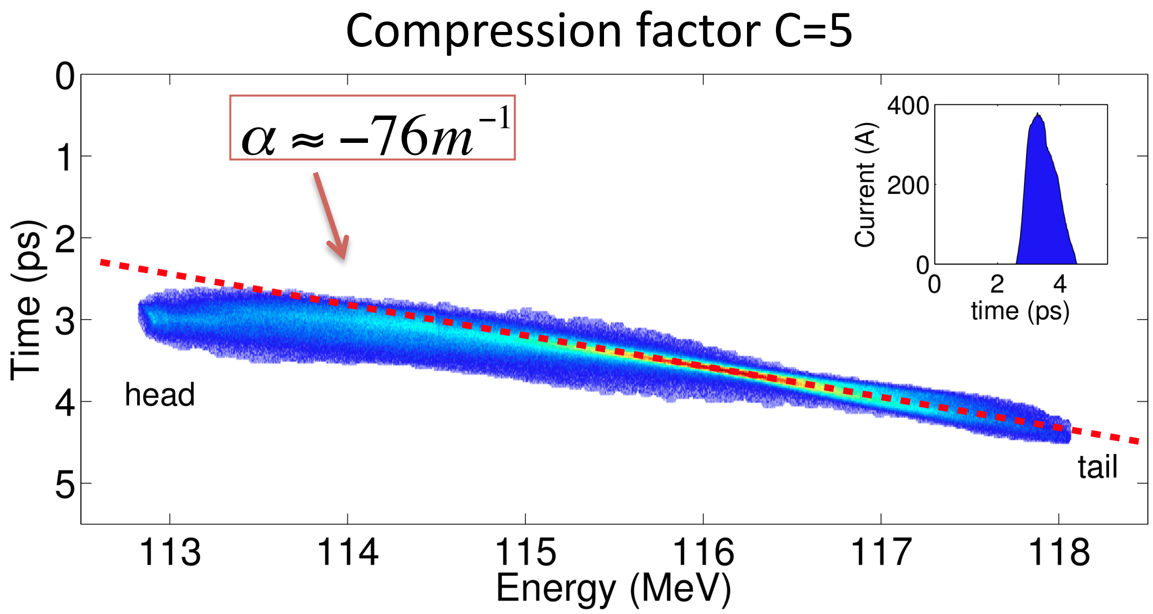
FEL diagnostic:



- Neutral density Filters;
- mirror for diagnostic;

- Entrance slit:
  - minimum aperture 20 µm,
  - maximum aperture 2 mm
- Entrance/exit arms: ≈1 m
- Three gratings:
  - 600 gr/mm,
  - 1200 gr/mm,
  - 2400 gr/mm
- Acceptance
  - 25 mrad × 25 mrad (1.4 deg × 1.4 deg)
- CCD detector (Roper Scientific)
  - Thinned and back illuminated
  - Pixel size 20 µm
  - 1340 × 1340 pixel
- Resolving element
  - 0.034 nm/pixel (600 gr/mm)
  - 0.017 nm/pixel (1200 gr/mm)
  - 0.0084 nm/pixel (2400 gr/mm)

Chirped beam for FEL experiments:



Beam energy	MeV	115.2
Rel. energy spread	slice/proj.%	0.6/1.15
Proj. emittances (x/y)	mm-mrad	2.7/3.0
Rms length	rms-ps	0.42
Peak current	A	380
$<\beta_x>=<\beta_y>$	m	1.5

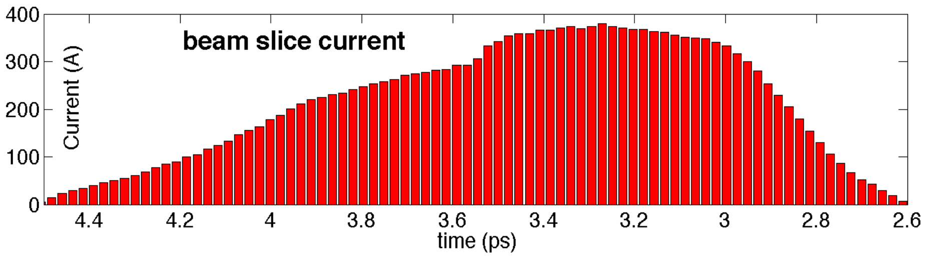
used as fitting variable in simulations ~ $1.7\text{x}10^{-3}$

use slice emittance values (+10%) measured without rf compression = $1.4\text{x}10^{-6}$m

FEL From chirped beam:

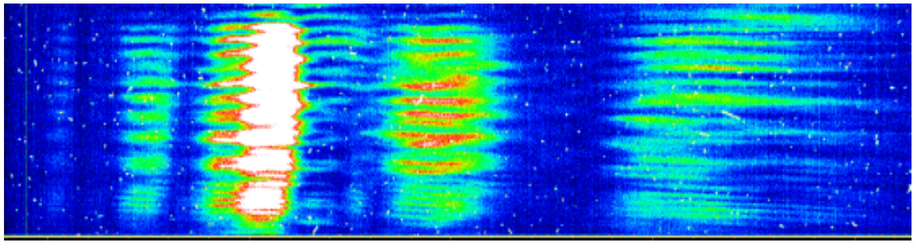
ELECTRON BEAM

$$\Delta\lambda_{FEL} = \lambda_0(2\frac{\Delta\gamma}{\gamma}) \approx 40nm$$



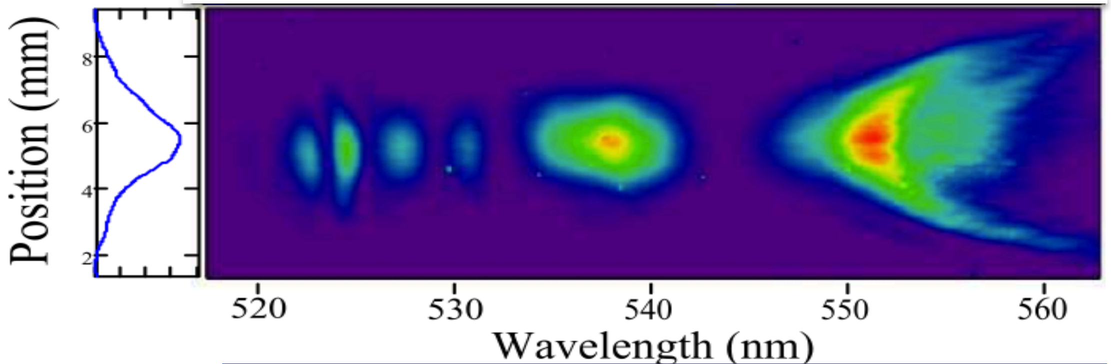
3 UM GAP SET

the spectrum expand over regions
outside the detector



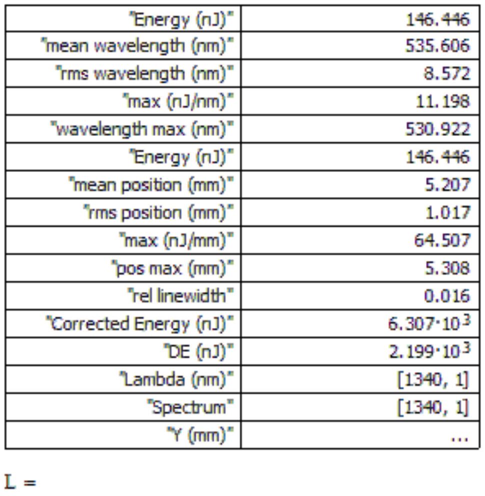
6 UM GAP SET

spectrometer slit closed
at 100um, 0.17nm resolution



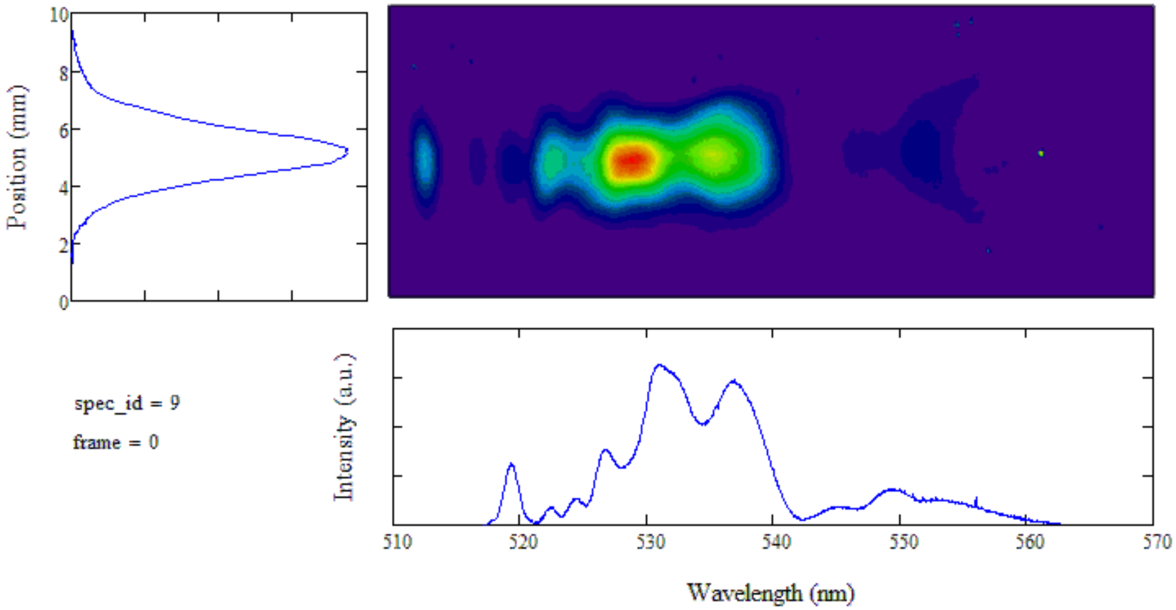
SASE WITH UNCHIRPED BEAM

Some statistics:



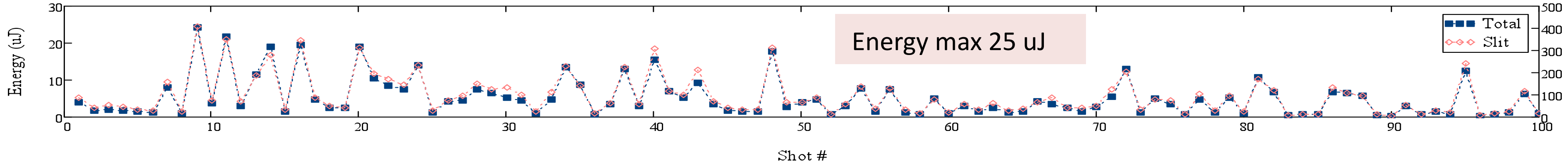
"Energy (nJ)"	146.446
"mean wavelength (nm)"	535.606
"rms wavelength (nm)"	8.572
"max (nJ/nm)"	11.198
"wavelength max (nm)"	530.922
"Energy (nJ)"	146.446
"mean position (mm)"	5.207
"rms position (mm)"	1.017
"max (nJ/mm)"	64.507
"pos max (mm)"	5.308
"rel linewidth"	0.016
"Corrected Energy (nJ)"	$6.307\cdot10^{3}$
"DE (nJ)"	$2.199\cdot10^{3}$
"Lambda (nm)"	[1340, 1]
"Spectrum"	[1340, 1]
"Y (mm)"	...

L =



spec_id = 9

frame = 0



Energy max 25 uJ

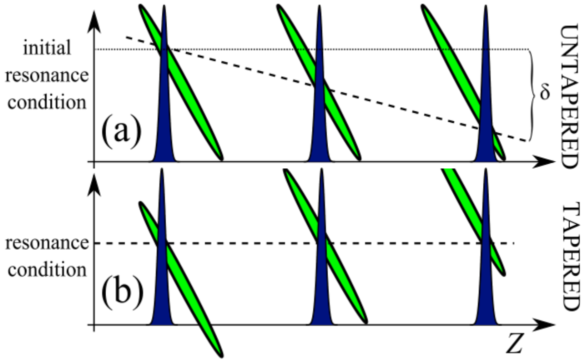
$$L_b^{tot} \approx 20-25\delta s_c ,L_{coh} \approx 5\delta s_c$$

number of spikes →

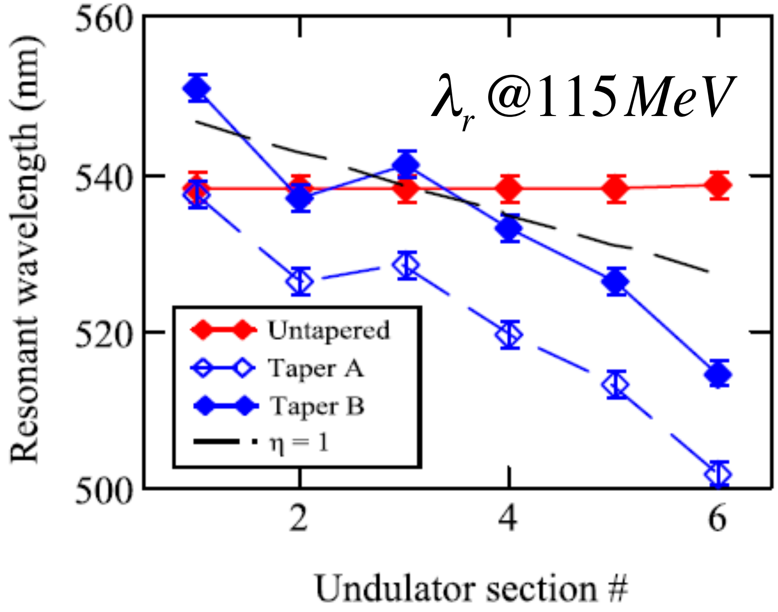
$$N_s = \frac{L_b^{tot}}{2\pi L_{coh}} \approx 4-5$$

Fluctuations in the number of spikes and Energy are affected by e- beam jitters (±1 deg with @ C=5 is ±20% bunch length jitter)

Undulator field tapering:

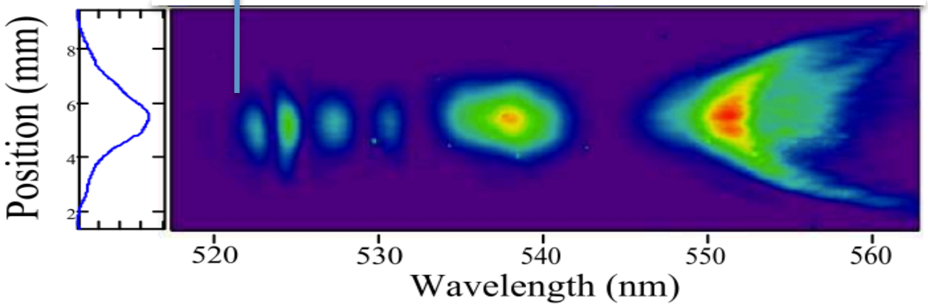


$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$



taper for radiation
starting from the tail

$$\gamma(s)\downarrow \Rightarrow K(s)\downarrow$$

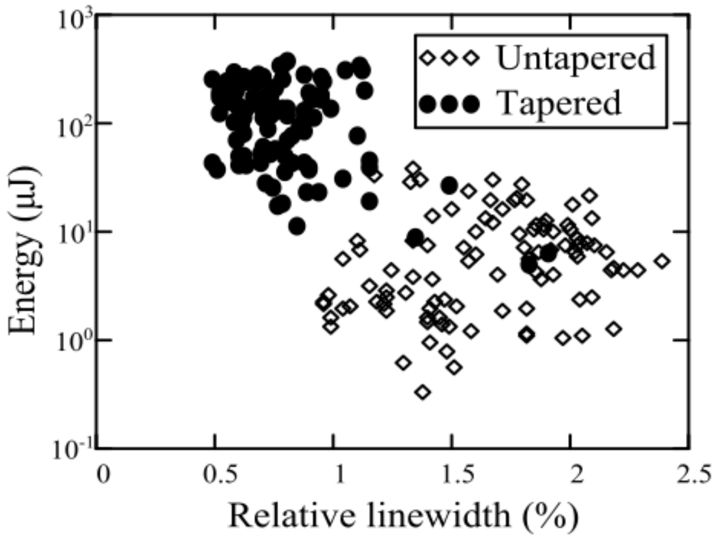


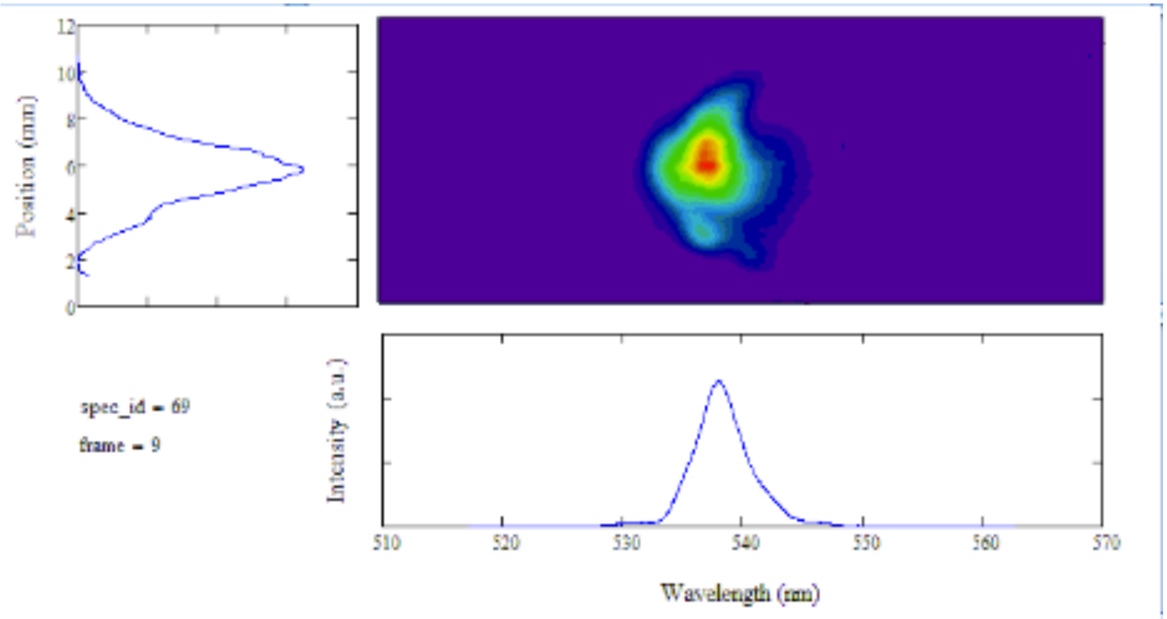
(A) Taper minimizing emission bandwidth (experimental procedure)

(B) Taper compensating the wavelength shift

Tapered FEL: Single spike evidence

About 50% of the shots have the spectrum composed by a single coherence region



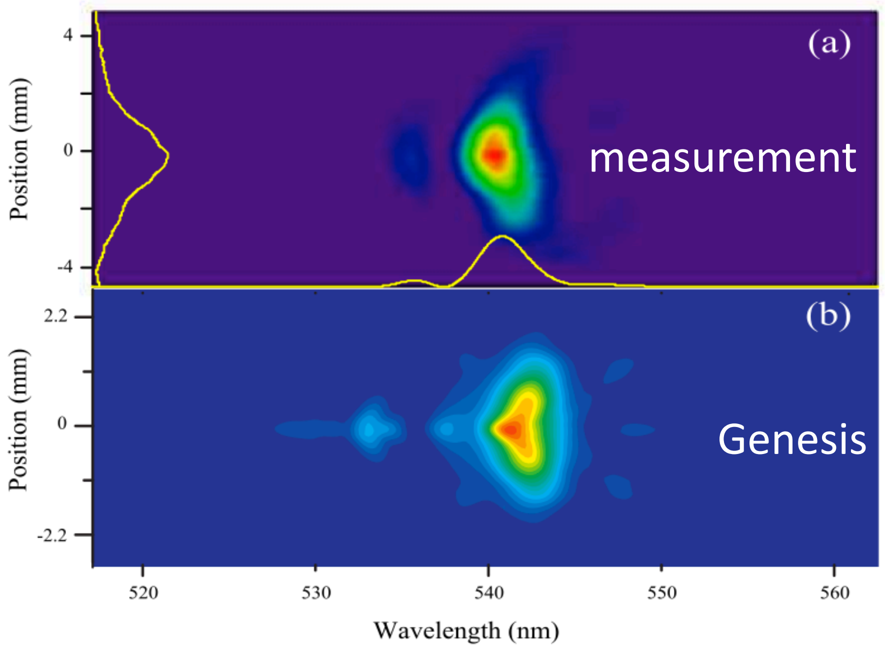


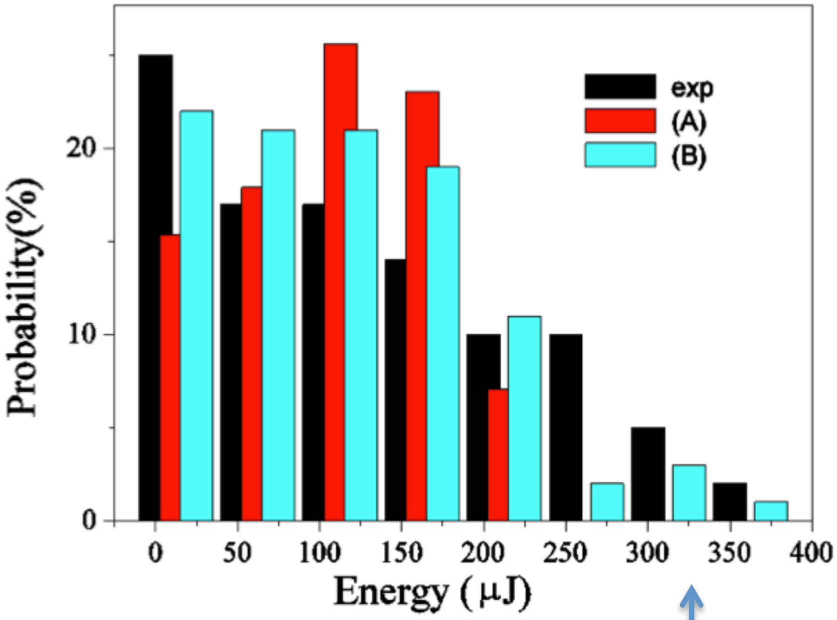
Energy up to 0.35 mJ (X20 respect to the untapered case)

1.45 nm bandwidth rms; If Fourier Limited L_b<100 fs, 300 μJ, → P_{peak}~GW

Comparison with simulations:

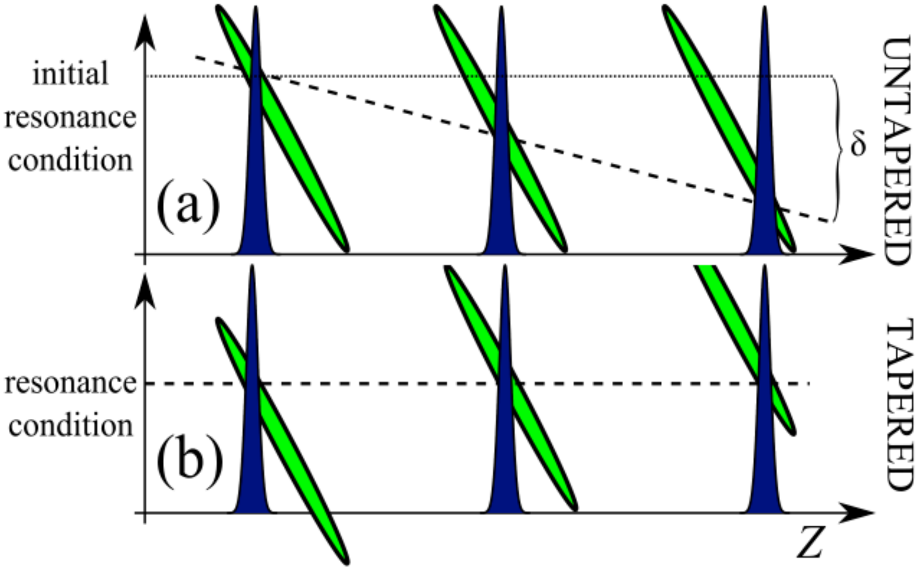
- Very good agreement with in the spectrum details between measurements and sims
- 11% fluctuation foreseen by Genesis in case of no beam fluctuations (just shot noise);
- Less single spike events in Genesis (30% Vs 50%)





A) Genesis sims with varying peak Current and bunch length (25%);
B) Genesis sims with varying also emittance (30%) and energy spread (10%)

Tapering analysis:



$$\alpha \approx -76m^{-1}$$

$$\frac{\partial E}{\partial s} \approx -8.7keV/\mu m$$

$$\omega_r = \frac{2\gamma^2}{1+\frac{K^2}{2}}\omega_u$$

$$\gamma(s) = \gamma_0(1+\alpha(s-s_0))$$

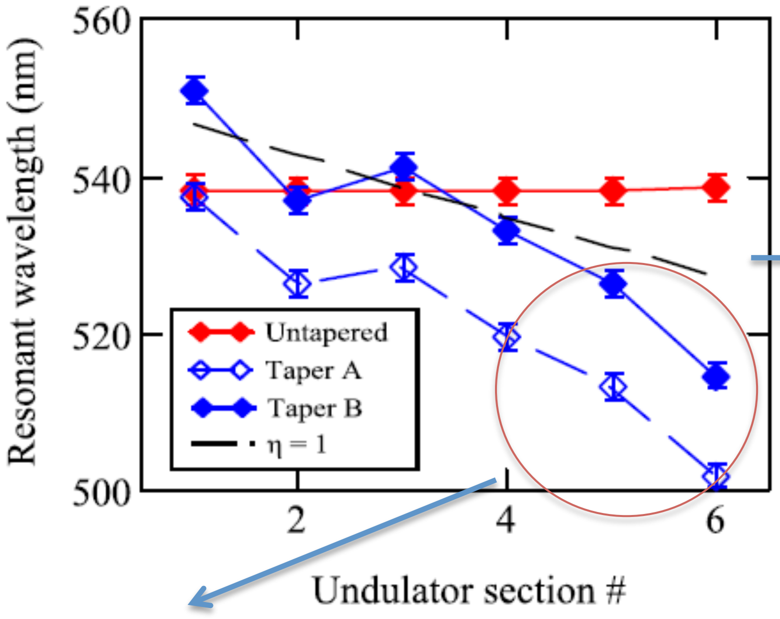
$$\Downarrow \beta_r = \eta(1-\beta_z)$$

$$\gamma(z) = \gamma_0(1+\alpha z\eta\frac{\omega_u}{\omega_r})$$

$$\Rightarrow$$

$$K(z) = 2\sqrt{[\gamma_0(1+\alpha z\eta\frac{\omega_u}{\omega_r})]^2\cdot\frac{\omega_u}{\omega_r}-\frac{1}{2}}$$

Resonance speed:



$$K(z) = 2\sqrt{[\gamma_0(1+\alpha z\eta\frac{\omega_u}{\omega_r})]^2\cdot\frac{\omega_u}{\omega_r} - \frac{1}{2}}$$

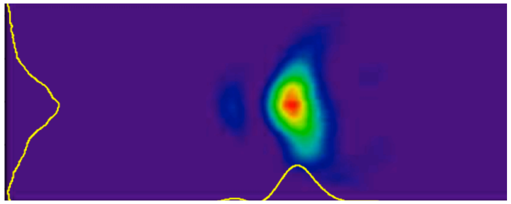
$\eta = 1$

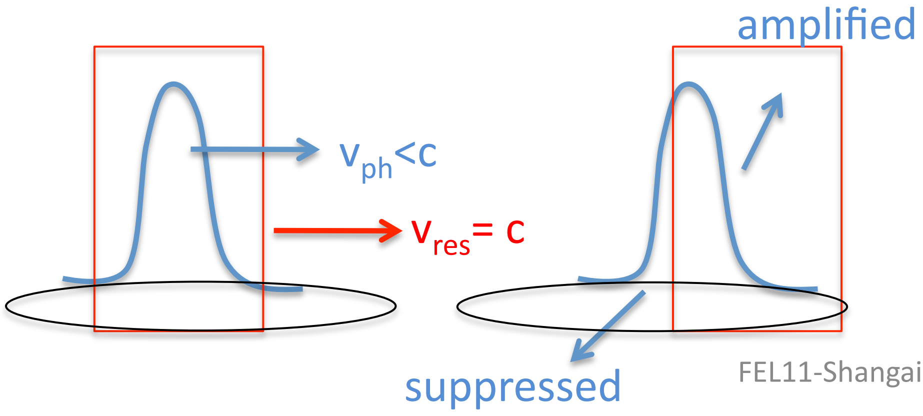
tapering in resonance with
photons traveling at c !!

beam energy loss
and LPS non linearities

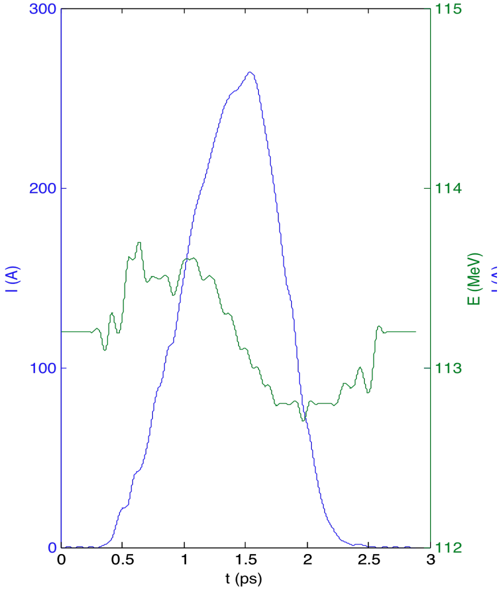
Slippage length ~ e-bunch length

single spectral region of coherence



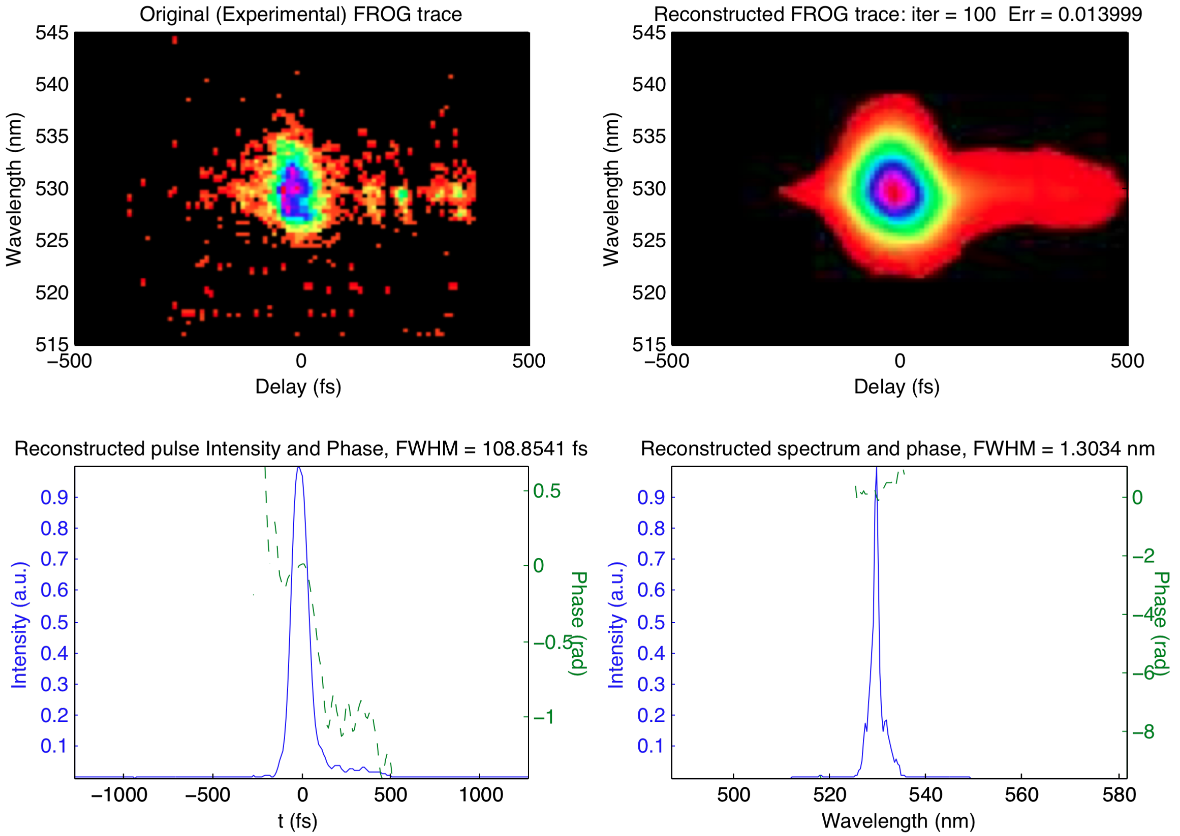


Preliminary FROG measurements:



e-beam

- $Q = 250$ pC
- $I_{peak} = 264$ A
- $E_0 = 113.068$ MeV
- Chirp = -2.484 keV/µm
- $\sigma_\gamma = 5\times10^{-3}$ (Max)
- $\varepsilon_{n,x(y)} = 2.27(1.6)$ mm mrad


Original (Experimental) FROG trace

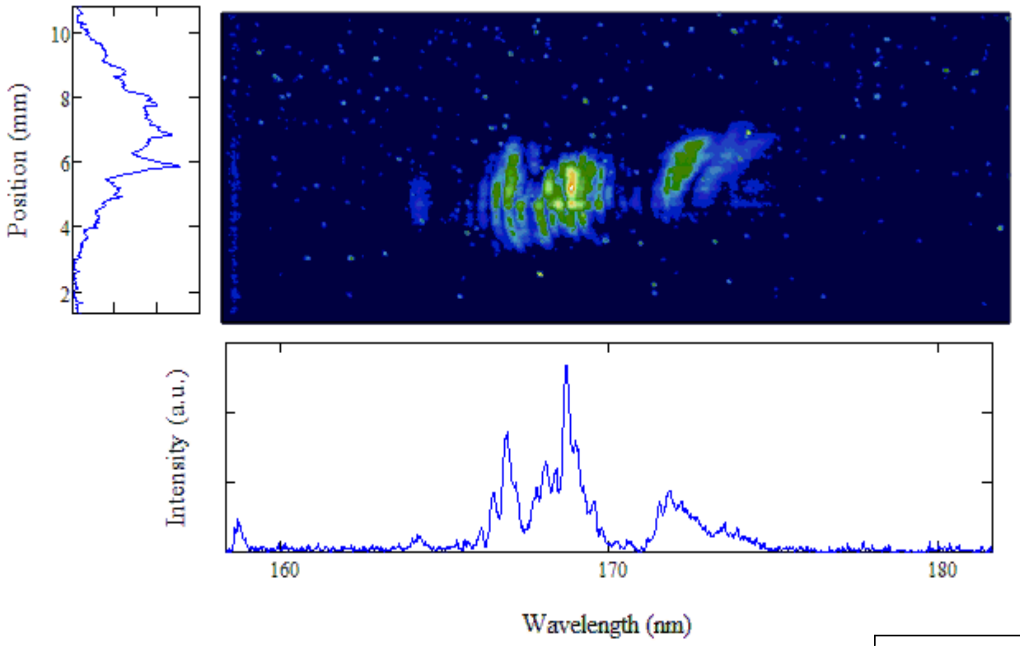
Reconstructed FROG trace: iter = 100 Err = 0.013999

Reconstructed pulse Intensity and Phase, FWHM = 108.8541 fs

Reconstructed spectrum and phase, FWHM = 1.3034 nm

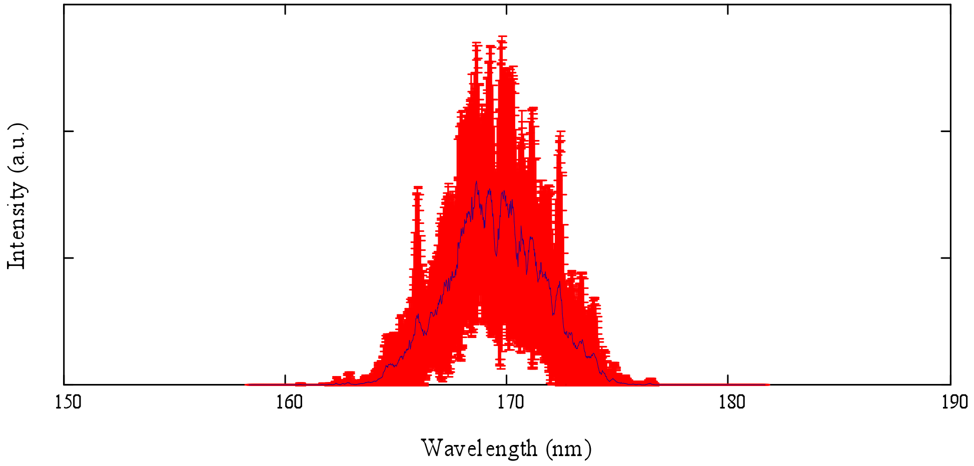
TBP = 0.9

Harmonics: 3rd

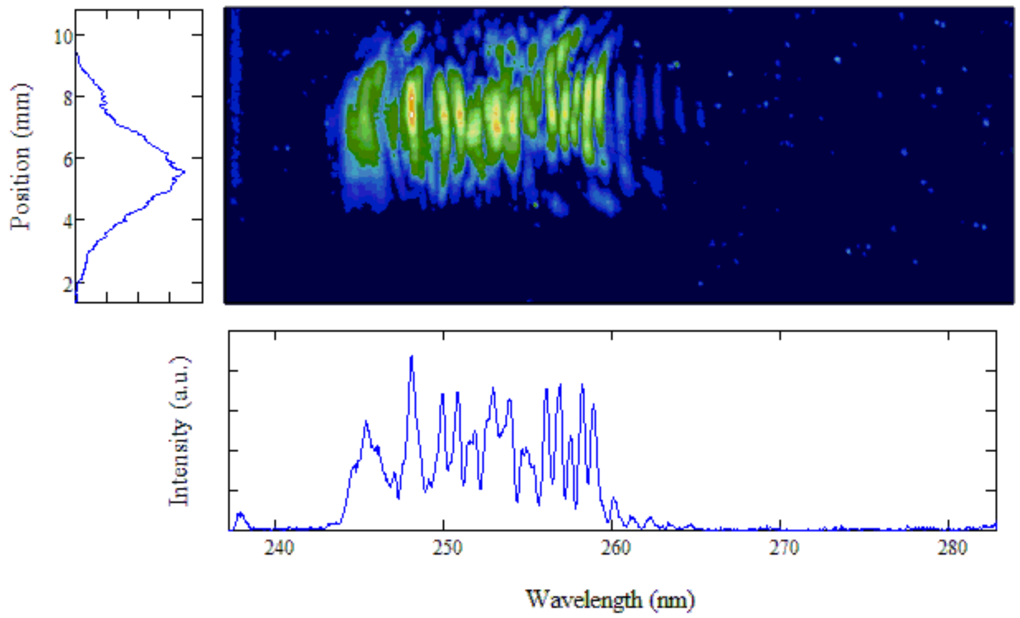


1st harmonic:
(31 ± 8) μJ
Δλ/λ=0.83%

- Mean pulse energy (230 ± 100) nJ
- Δλ/λ=1.3%
- blue curve: mean spectrum over 100 shots
- red band: ± 1 rms



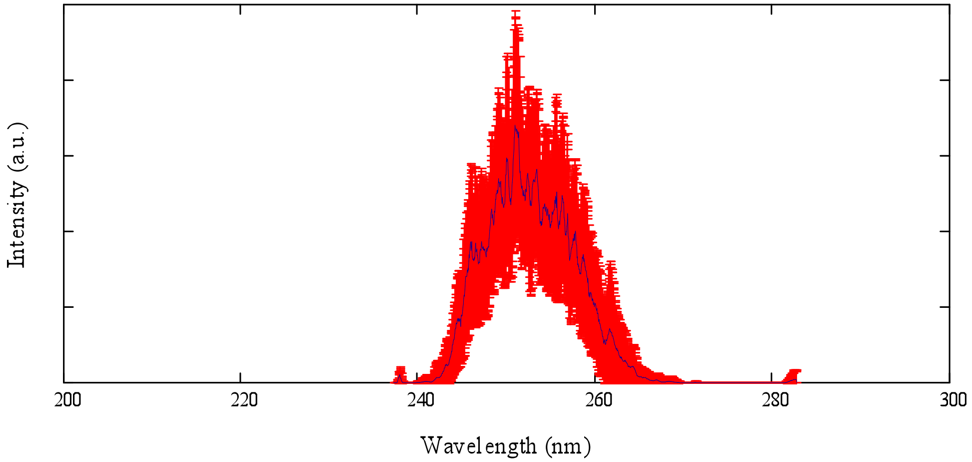
Harmonics: 2nd



Possible causes:

- saturation
- electron beam x-t correlations
- undulator fields
- spectrometer misalignments

- Mean pulse energy (100 ± 25) nJ
- Δλ/λ=1.6%
- blue curve: mean spectrum over 100 shots
- red band: ± 1 rms



Conclusions:

- Electron beam chirping is a convenient way of manipulating the electron beam to enhance the FEL light properties

- Strong chirped FEL pulses may be used in a variety of different ways to control the pulse duration, increase the peak power, or seed a downstream amplifier.

- Trains of single spike pulses may be generated, separated both in time and frequency.

- Combining a chirped electron beam with a tapered undulator may allows gain selection and control along the electron bunch

- In the presented experiment this combination has been used to obtain high energy single spike pulses. (300 uJ/100 fs/1GW)

Thank you
謝謝