

# SPARC\_LAB collaboration:

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CNR

UCLA

# Observation of time-domain modulation of FEL pulses by multi- peaked electron energy spectrum

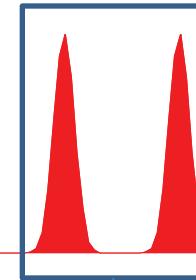
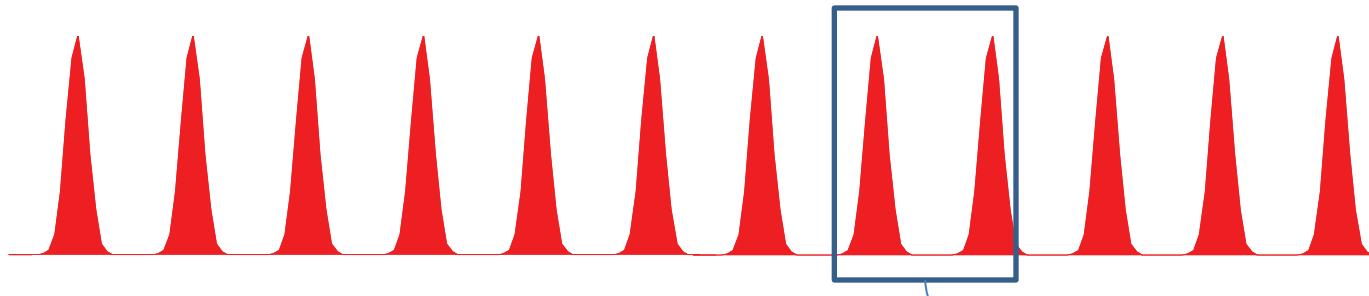
V. Petrillo

On behalf of the SPARC\_LAB team

# Outline

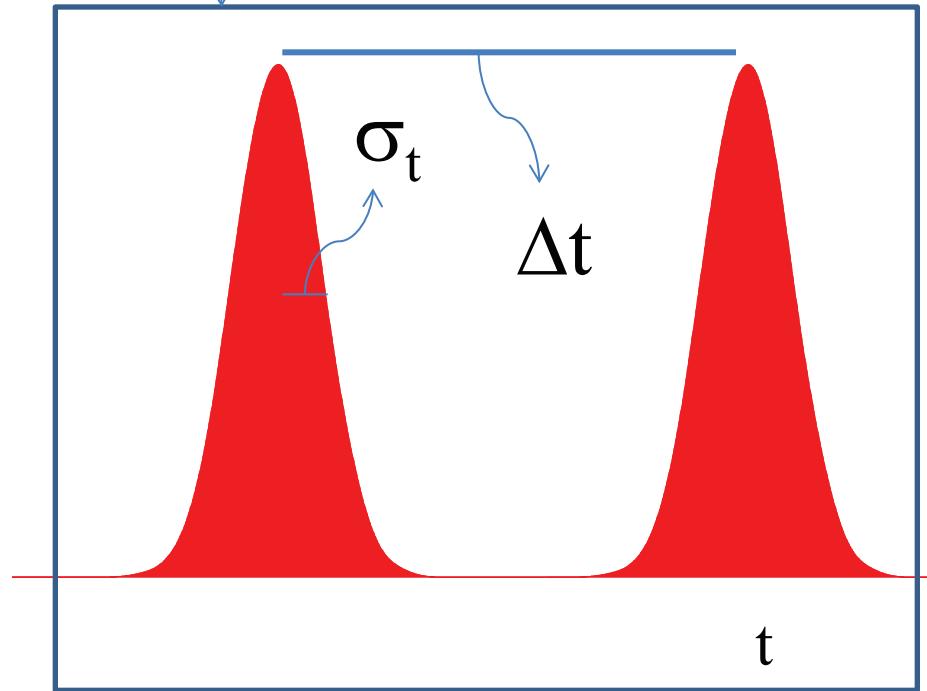
- INTRODUCTION
  - Scientific Motivation
- METHOD
  - Laser comb technique-velocity bunching-SASE single-spike emission
  - Advantages, extrapolations and limitations
- RECENT FEL EXPERIMENTS AT SPARC\_LAB
  - Two-color FEL radiation
  - FEL pulse train generation
- CONCLUSIONS

# Stroboscopic light



Regular sequence of spikes equally spaced in time

Applications in the imaging of fast phenomena





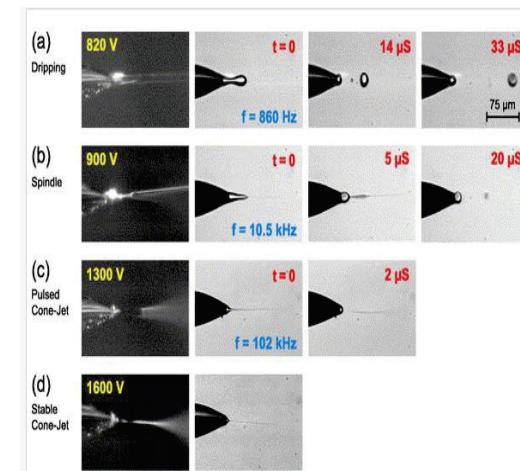
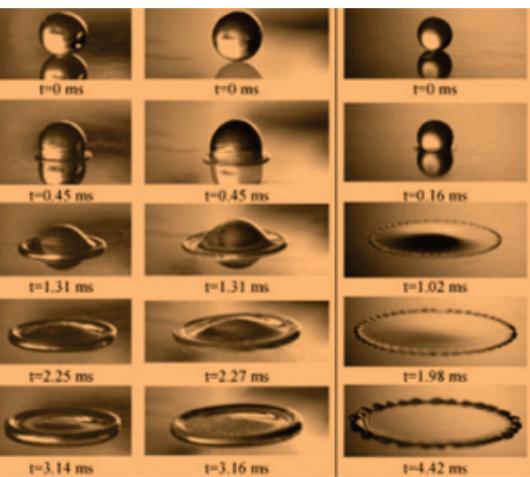
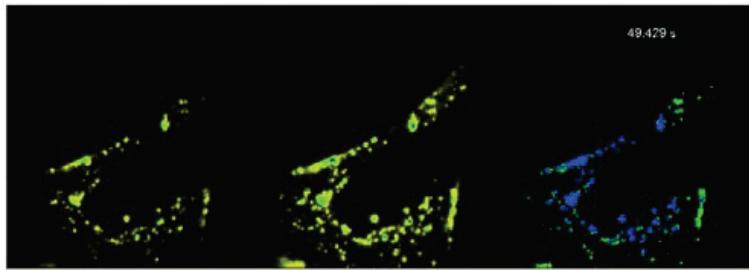
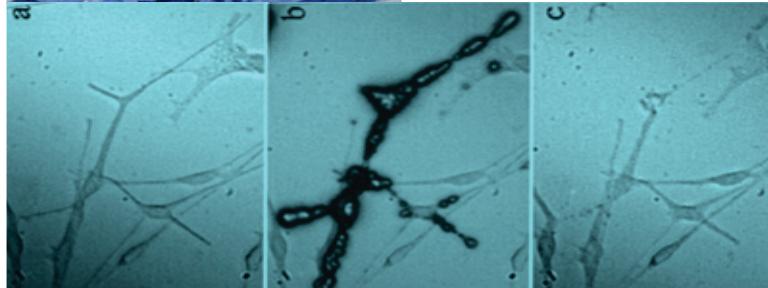
Giacomo Balla  
Volo di rondini  
1913  
MoMA ,  
New York



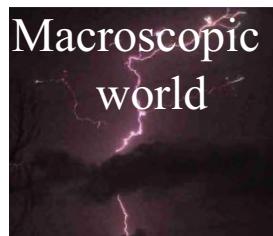
Giacomo Balla  
Dinamica di un cane in movimento  
1912  
Albright-Knox Art Gallery ,  
Buffalo



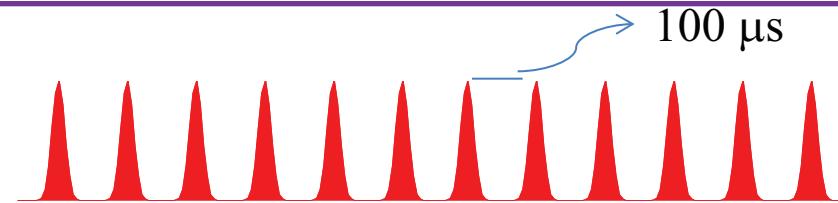
Gino Severini  
Danzatrice in Blu  
1912  
Collezione Mattioli, Milano



# Stroboscopy



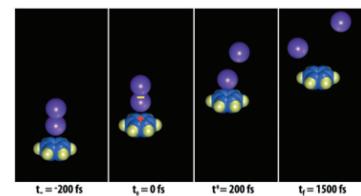
visible light  
 $10^4$  frame/s



Macroscopic objects

protein motion  
nanostructured objects

fundamental dynamics  
of the chemical bond,  
photosynthesis  
vision



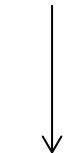
dissociation reactions  
atomic motion

electron motion in outer shells of atoms

electron motion in inner shells of atoms

nuclear dynamics

Visible light

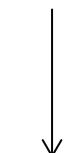


hundreds microseconds

nanoseconds

picoseconds

UV



femtoseconds

X rays

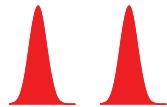
tens-hundreds of attoseconds

Single attosecond

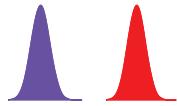
zeptoseconds

# Pump and probe

First pulse excites a phenomenon, second detects it.



Difference in frequency and intensity.



The time evolution is analyzed by increasing the time delay between the pump and the probe.



Typical examples:  
Laser induced fluorescence  
Mass spectroscopy



Other application of two color and multipeaked radiation:  
Formation of plasma waves  
Differential color imaging



# Proposals, ideas and experiments

A. A. Zholents and G. Penn, Nucl. Inst. and Meth. A 612, 254(2010).

D. Xiang, Z. Huang, G. Stupakov, Phys. Rev. ST-AB 12, 060701 (2009).

N.R. Thompson and B. W. J. McNeil ,PRL 100, 203901 (2008)

D. J. Dunning, B. McNeil, and N. Thompson Phys. Rev. Lett. 110, 104801 (2013)

A. A. Lutman, R. Coffee, Y. Ding, Z. Huang, J. Krzywinski, T. Maxwell, M. Messerschmidt, and H.-D. Nuhn Phys. Rev. Lett. 110, 134801 (2013)

G. De Ninno, B. Mahieu, E. Allaria, L. Giannessi, and S. Spampinati Phys . Rev. Lett. 110, 064801 (2013)

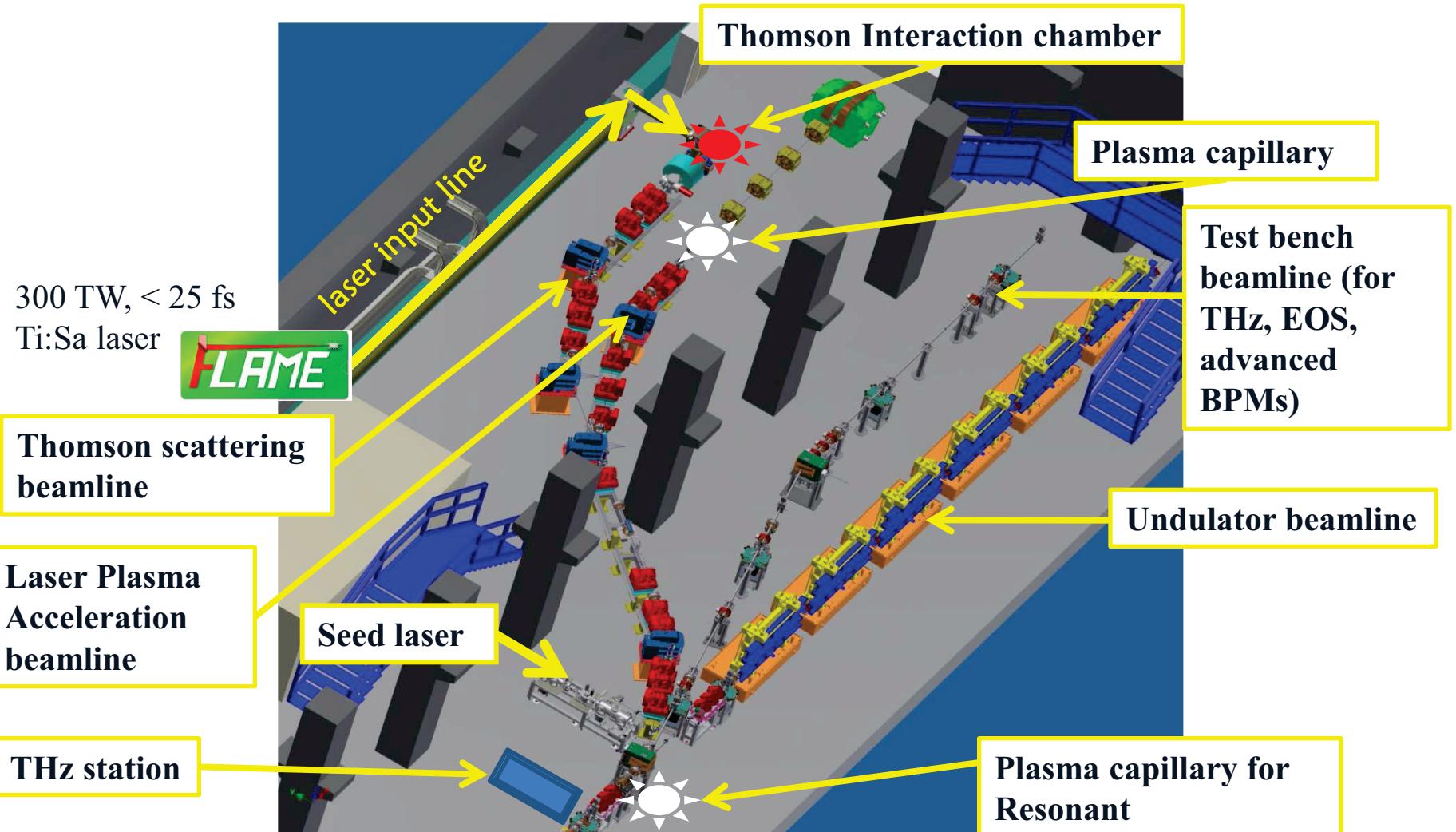
V. Petrillo, M.P. Anania,M. Artioli, A. Bacci, M, Bellaveglia, E. Chiadroni, A.Cianchi et al. , Phys. Rev. Lett. (2013) in press

A. Marinelli et al. Phys. Rev. Lett. (2013) in press

F. Capotondi et al. Nat. Communication (2013) in press

Experiment at LCLS with two beams compressed by magnetic chicane. Private comm. by A. Marinelli

# The SPARC\_LAB Facility



# The SPARC Free Electron Laser



UCLA



Period	2.8 cm
Undulator length	2.156.m
No of Periods	77
Gap (nom./min/max)	0.958 / 0.6 / 2.5 cm
K (nom./max/min)	2.145 / 3.2 / 0.38
Remanent field	1.31 T
Blocks per period	4
Block size (h x l x w)	2 x 0.7 x 5 cm

Diagnostic  
and  
Matching

180 MeV S-band linac  
SLAC constant gradient design  
Solenoid ~300 G  
Accelerating field ~20 MV/m

12 m

Long  
Solenoids

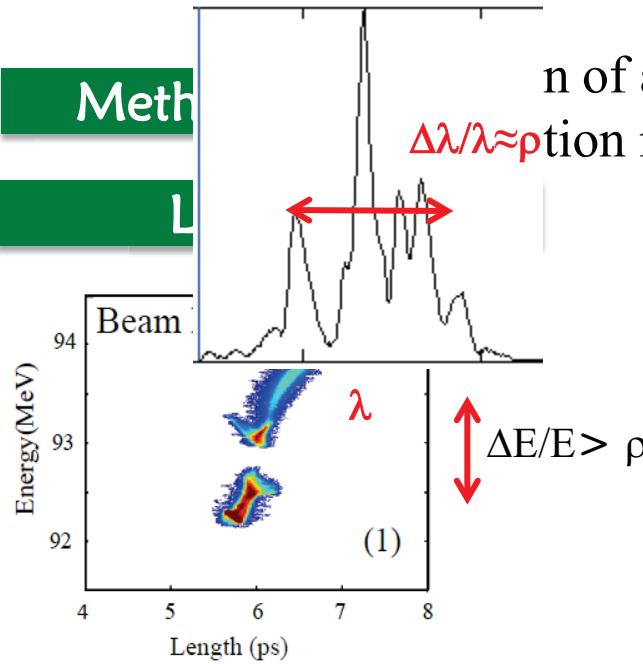
S-band GUN  
UCLA/BNL  
design  
Solenoid ~3 kG  
Input Power 14  
MW  
Max Acc. Field @  
cathode ~130  
MV/m

14 m

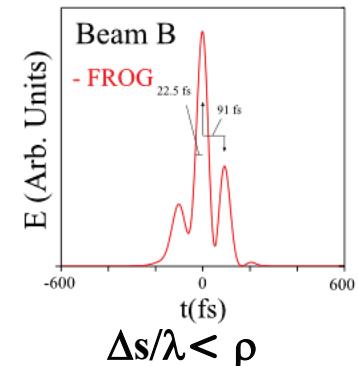
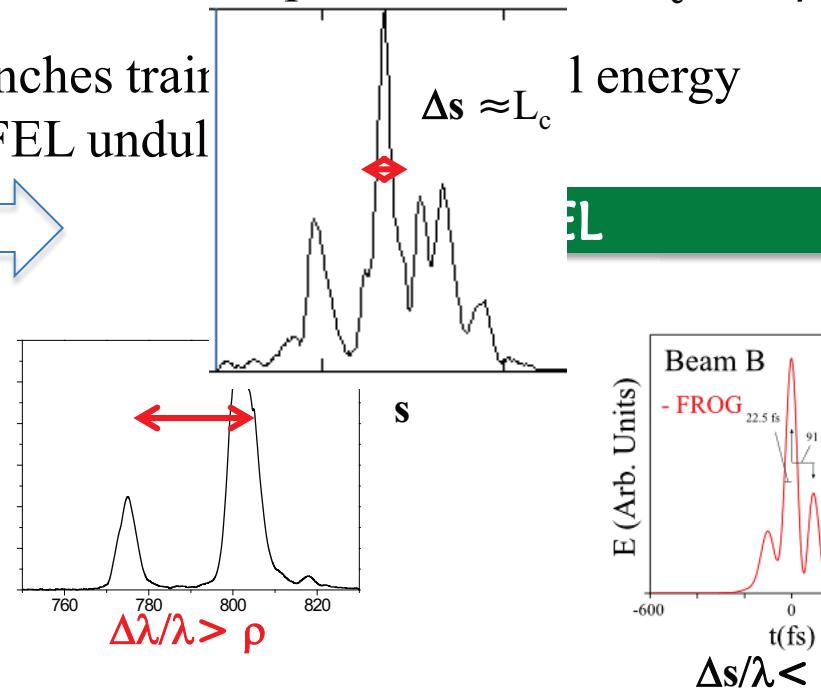
Beam energy	90 – 180 MeV
Bunch charge	50 – 500 pC
Rep. rate	10 Hz
$\epsilon_n$	< 2 mm-mrad
$\sigma_\gamma$	0.05% - 1%
Laser Pulse length	200 fs – 5 ps (FWHM)

# Two color and multipeaked FEL radiation @ SPARC

FEL relative natural bandwidth  $\approx \rho$



Shortest spatial structures  $L_c \approx \lambda/\rho$



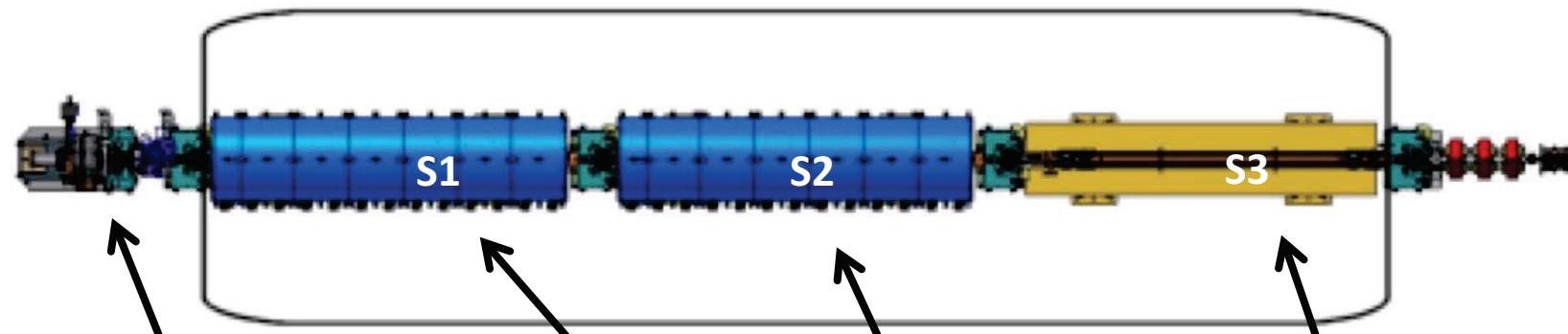
Sub-bunches energy spread  $\approx \rho$   
Sub-bunches length smaller than  
the cooperation length  
 $\Rightarrow$  Single spike operation

SASE FEL from **separate and nearly independent electron distributions**  
Gain can be obtained  
at two separate frequencies  $> \rho$

Regular spatial structures  
shorter than  $L_c$   
 $\Delta s/\lambda < \rho$

# Knobs for beam manipulation in velocity bunching regime

- Time and energy separation range is fixed by **crystal and Q**
  - Two bunches: separation=4.27 ps, rms single bunch length=0.093 ps, total charge~160 pC
- Inside this range, their values are fixed by **Linac phases S1 and S3**
- Quality of the electron beam is improved by moving **Gun phase and S2**



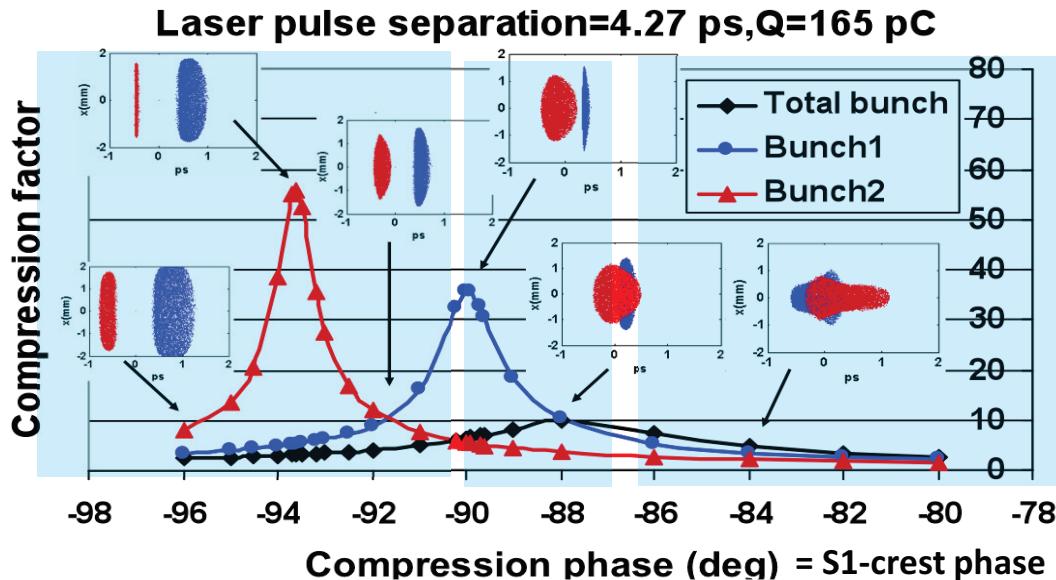
Fine tuning on bunches and energy separation  
GUN phase

**Time separation:**  
S1 phase

**Energy spread:**  
S2 phase

**Energy separation:**  
S3 phase

# Simulated compression curve



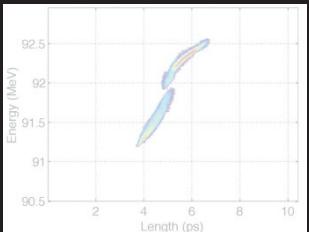
## VB-Moderate compression

energy separated and temporally modulated bunches

### S1,S2,S3 work off-crest:

S1 phase controls time separation

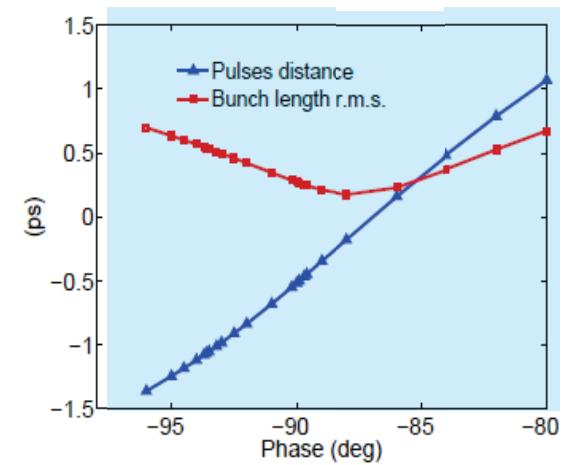
S2 and S3 control single bunches energy spread,  
fine tuning of final energy



## VB-Maximum Compression

energy separated and temp  
superimposed bunches

## TSTEP simulation by C. Ronsivalle

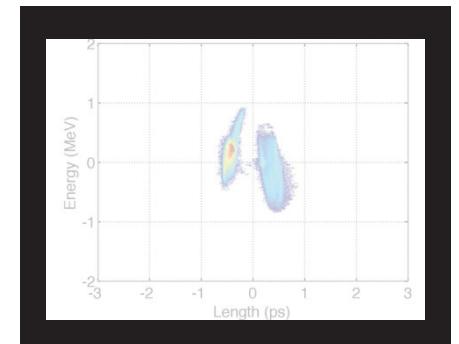
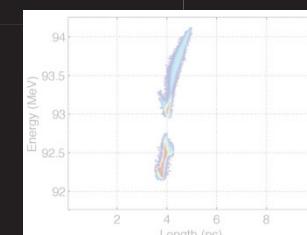


## VB-Over compression

energy and time separated bunches

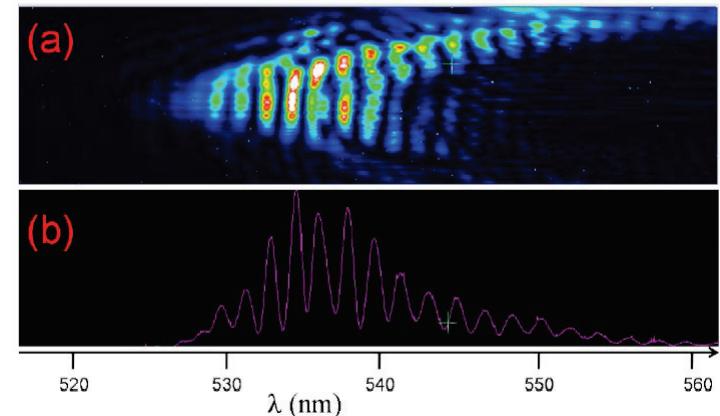
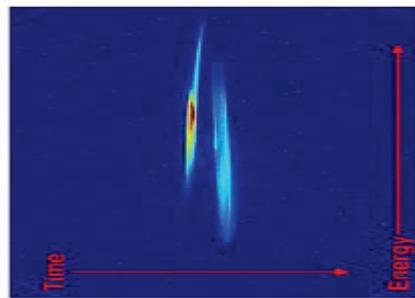
same energy – separated in time bunches

time separation is controlled by S1 phase,  
S3 is used for energy difference compensation



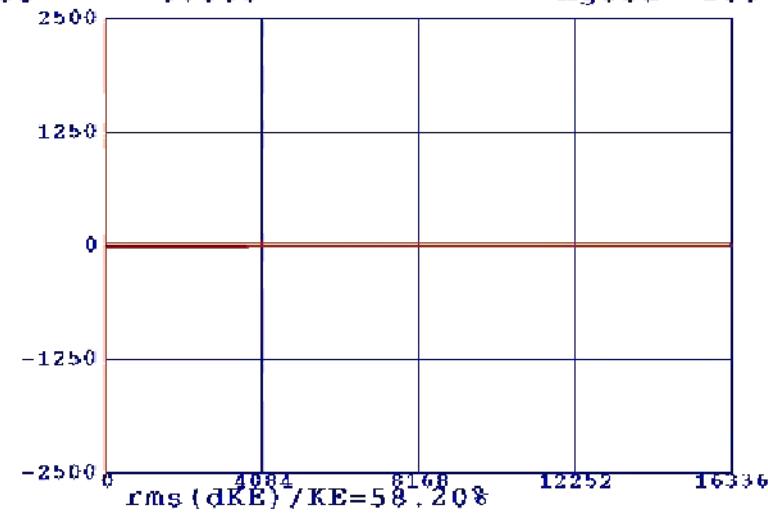
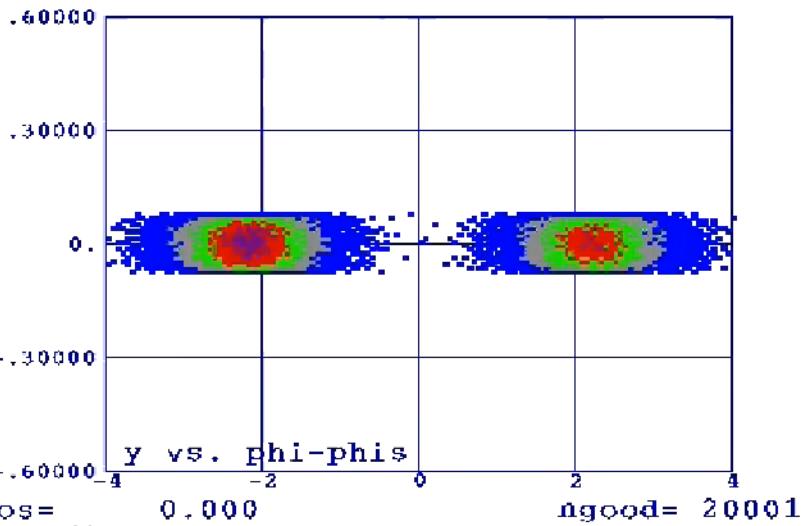
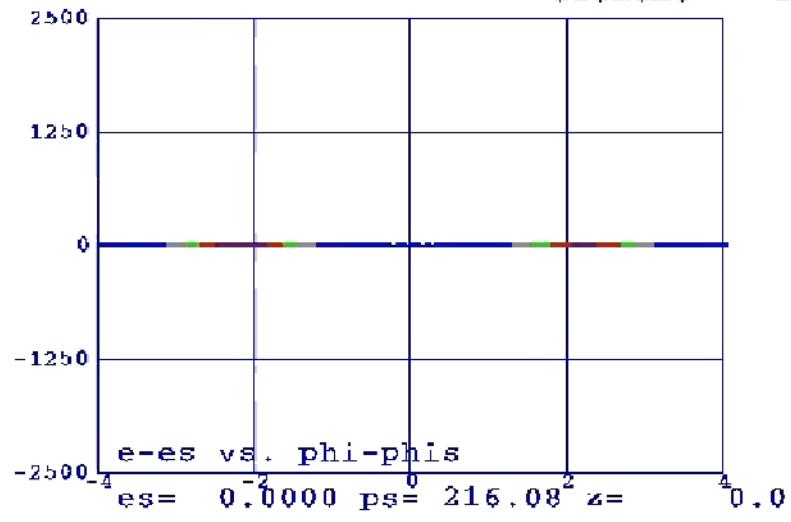
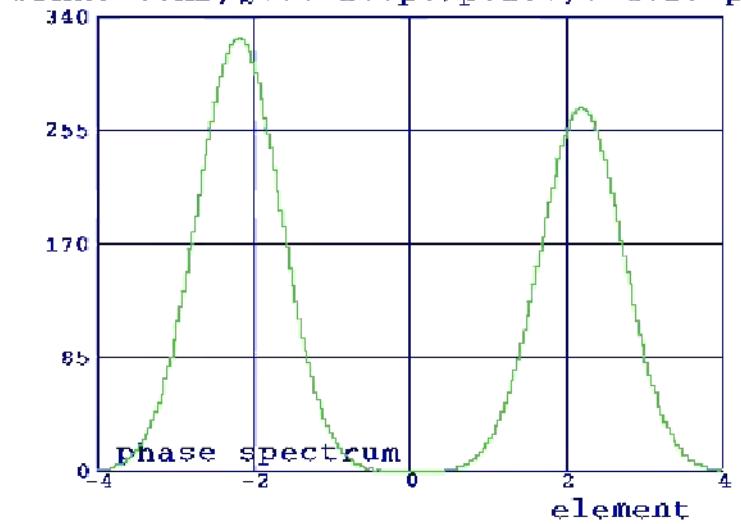
# Over compression regime

- Possibility of generating two pulses same energy and split in time

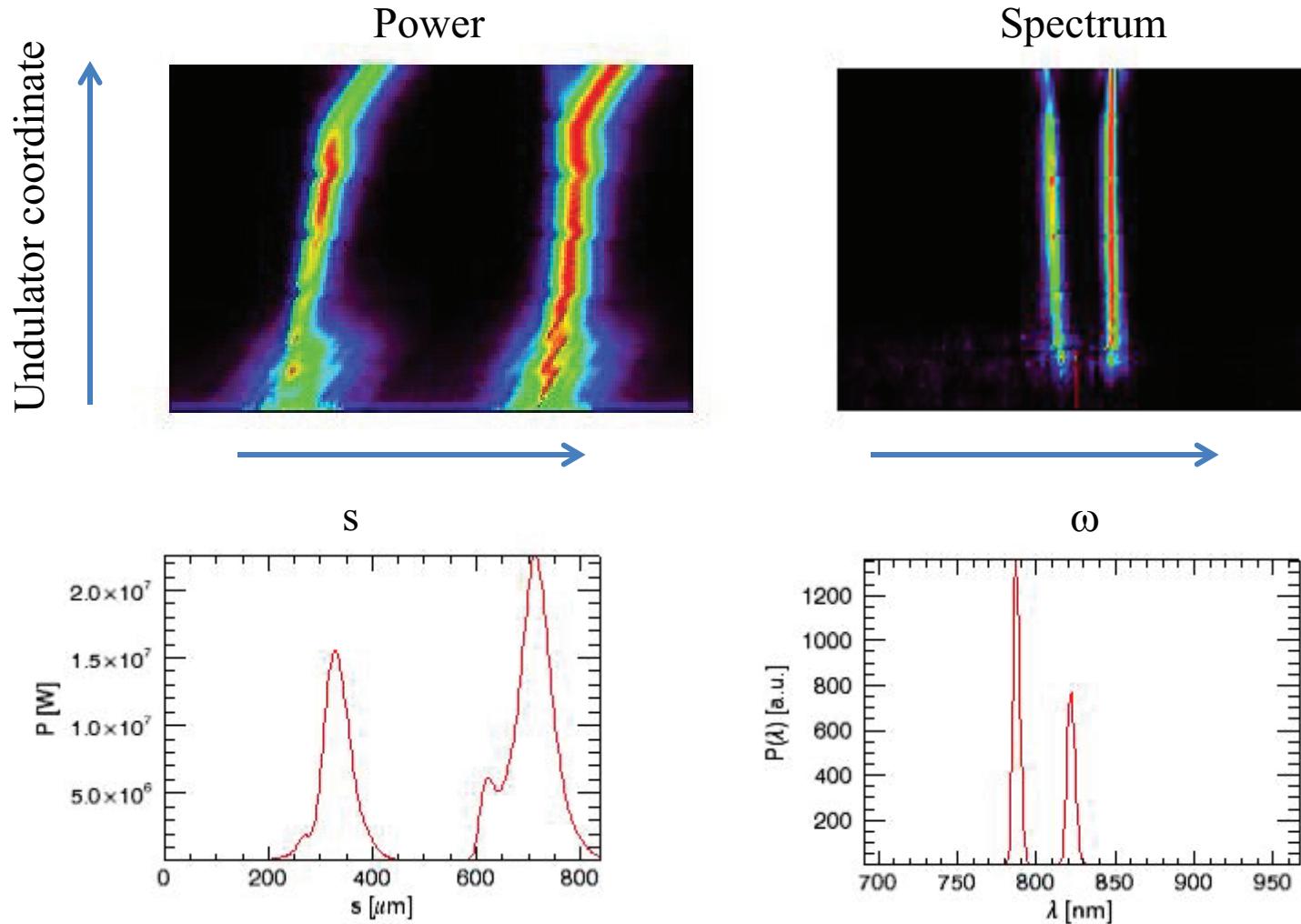


- Possibility of generating two pulses split both in time and in energy for pump and probe

SPARC COMB, Qtot=166pC/pulse, d=4.27 psec

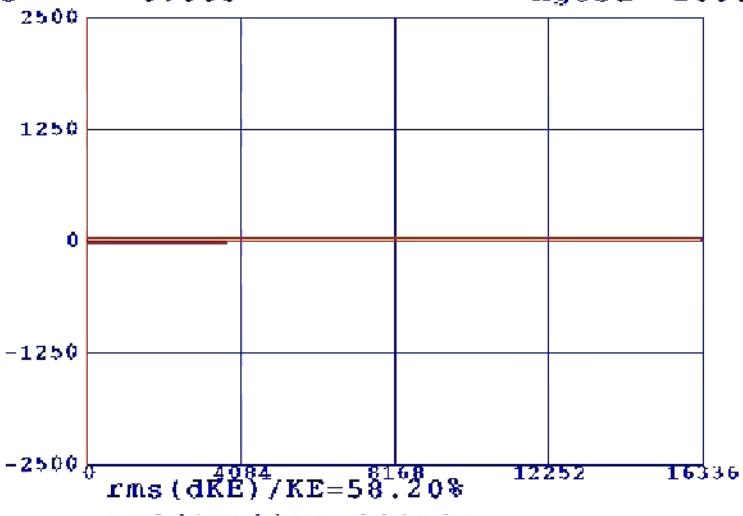
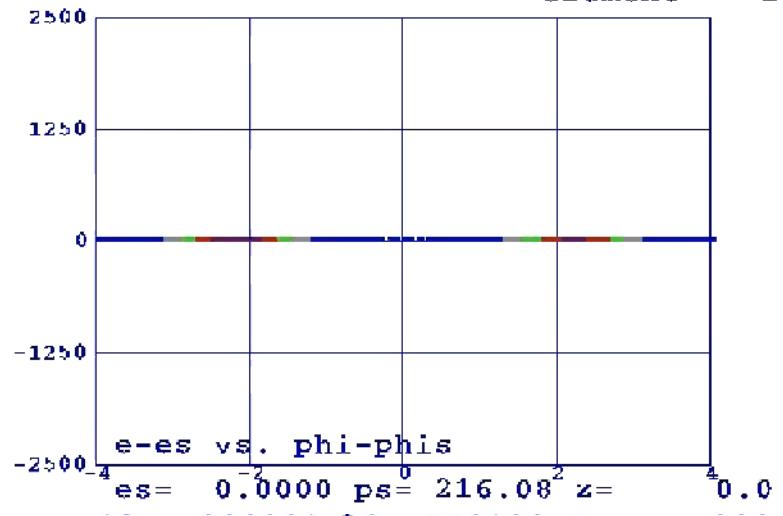
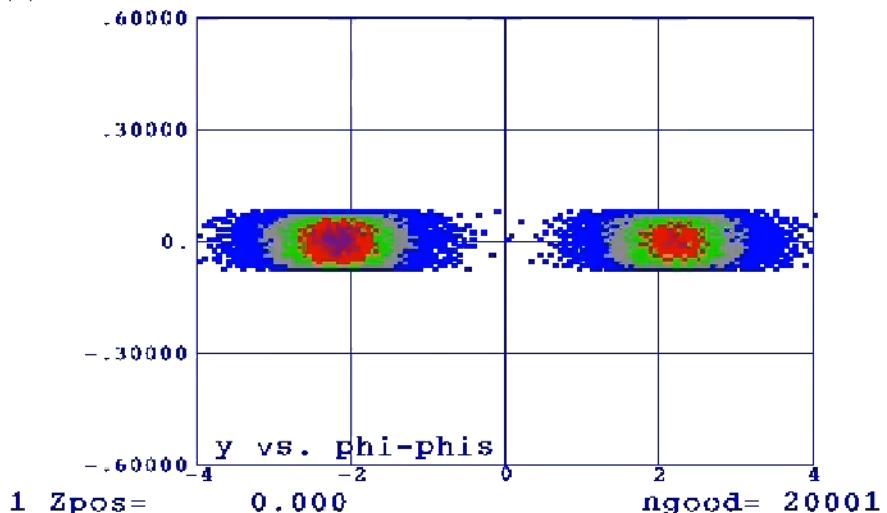
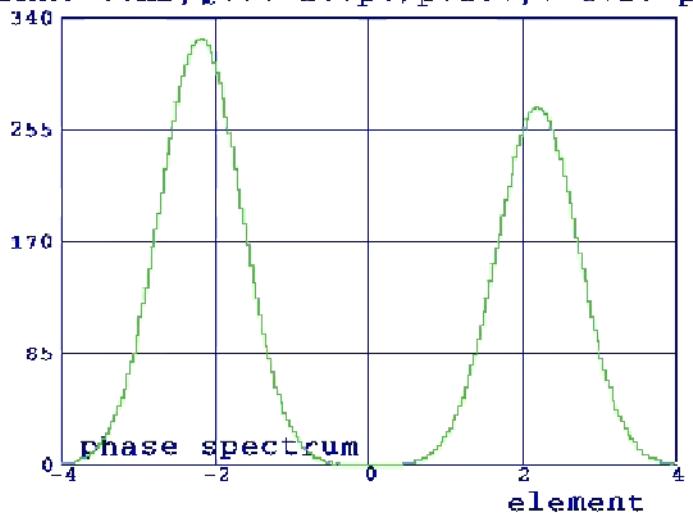


# Over compression regime: Genesis 1.3 simulation

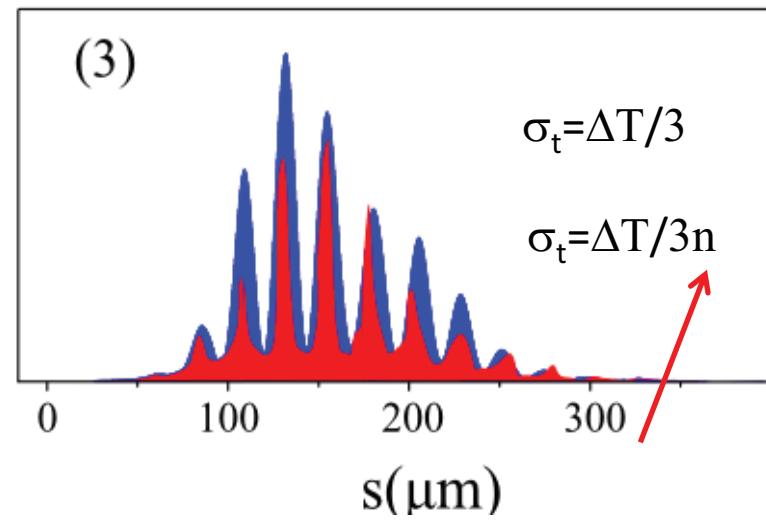
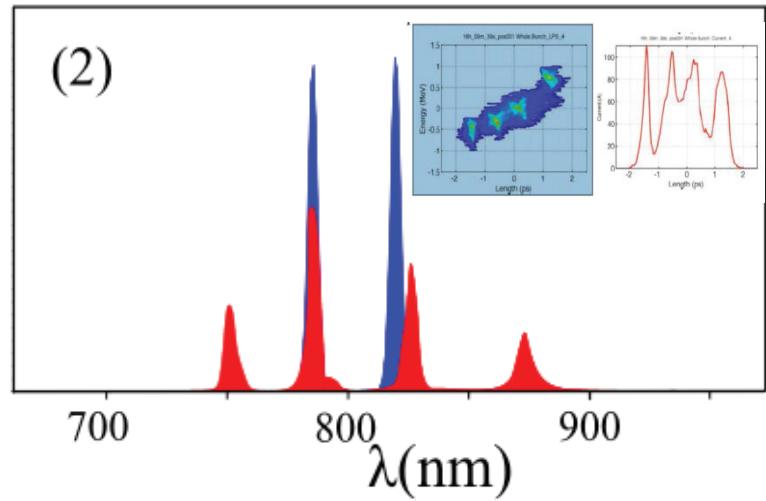
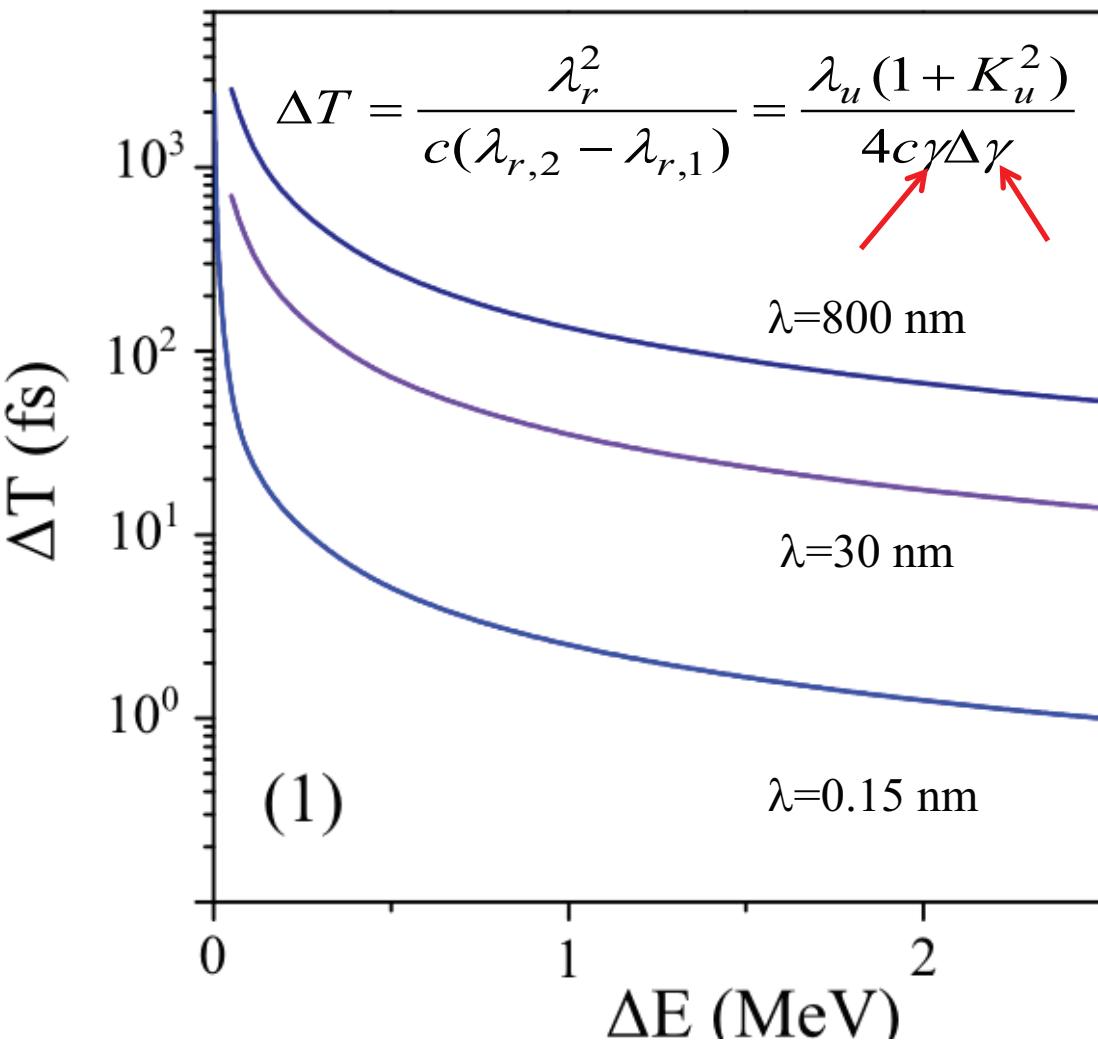


# Around the maximum compression

SPARC COMB, Qtot=166pC/pulse, d=4.27 psec

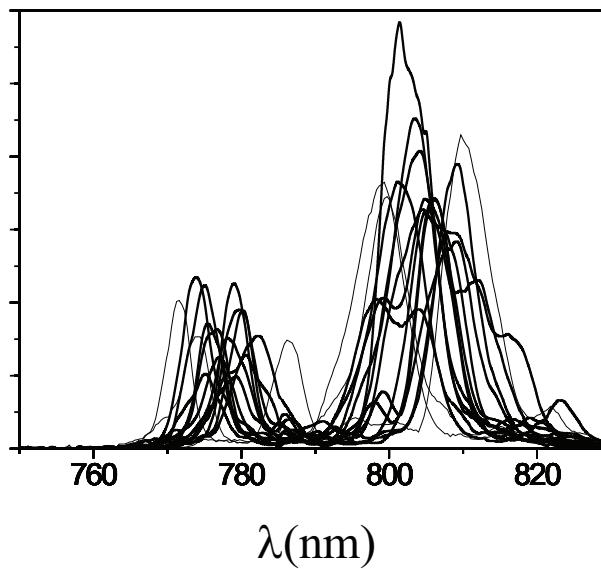


# Possible extrapolations to larger frequencies and shorter pulses



# Limitation in coherence

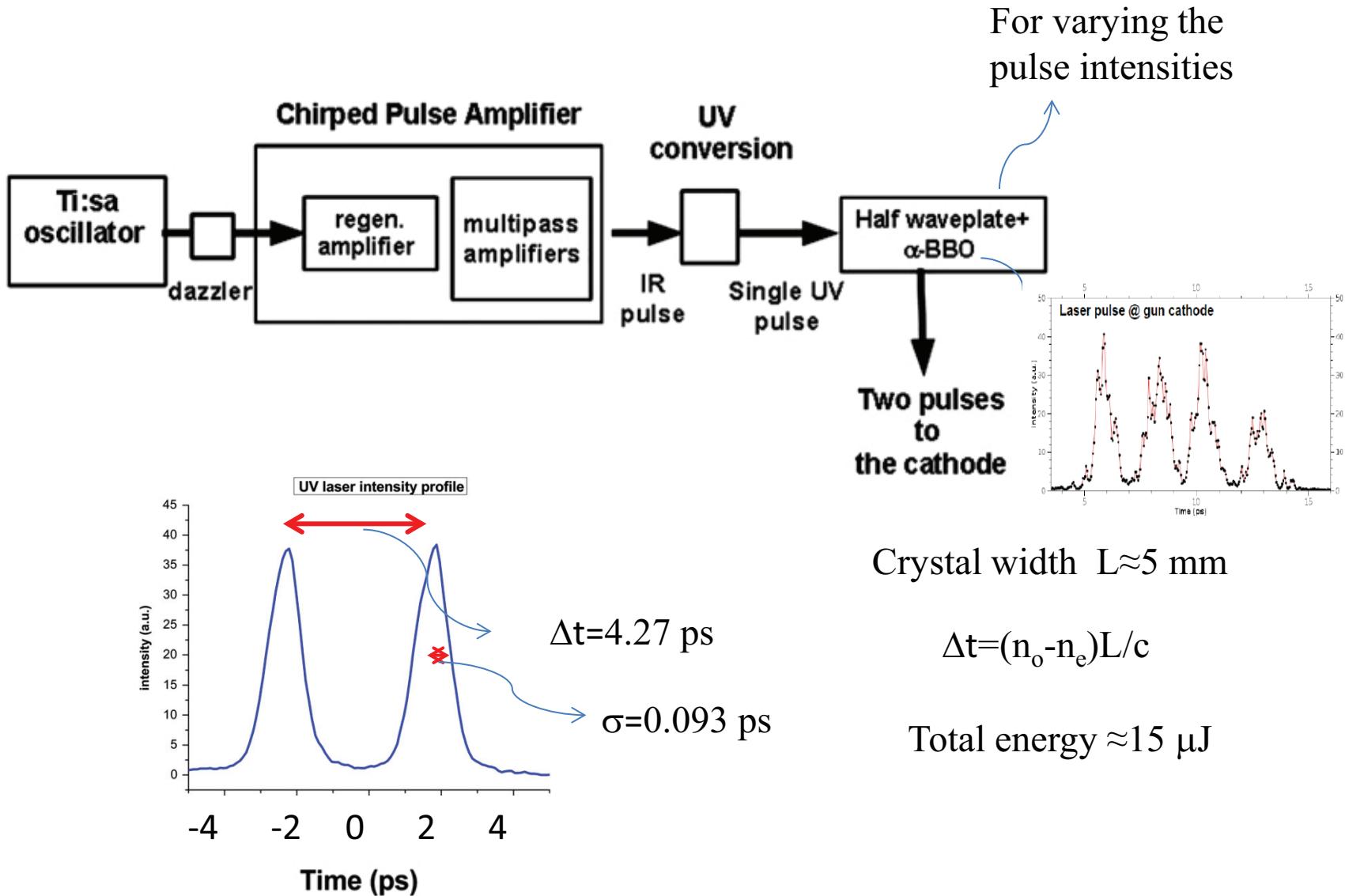
Being based on the FEL SASE regime, the method does not produce coherent light, in a statistical sense.



Each field realization has different intensity, phase, pulse separation, . . . , due to jitters of the electron beam and SASE fluctuations.

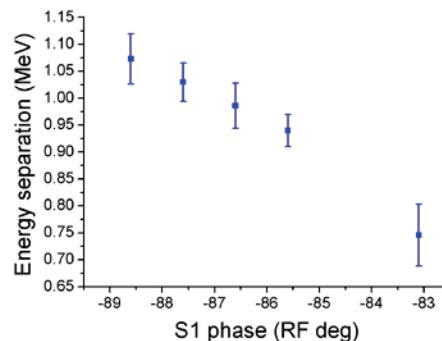
However, inside each single shot, intensity, phase, pulse separation and width are correlated or constant.

# The experiment: the laser comb technique

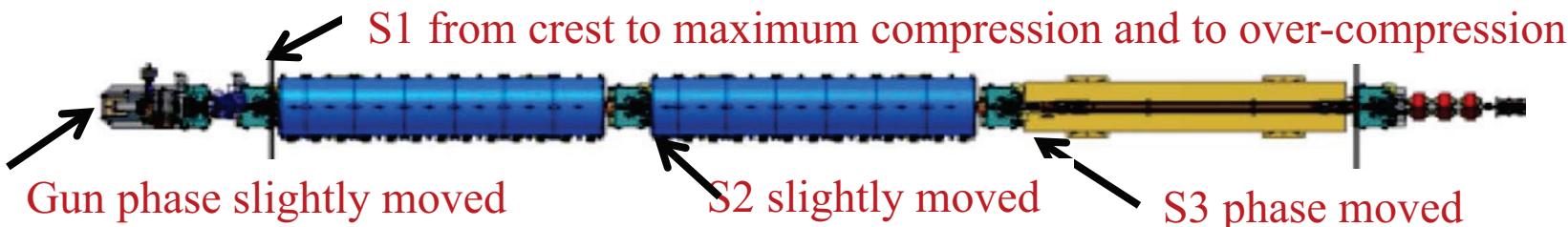
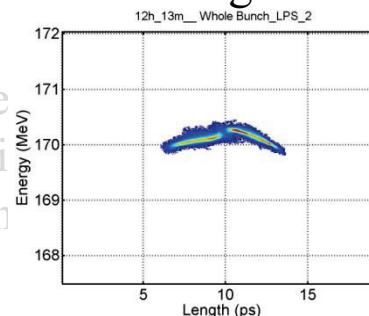


# The experiment: procedure for the compression

- The bunch train is characterized by the phase of the first crest of the RF linac (0 deg)
- Then the phase of the first pulse is varied to achieve maximum compression (90°) with full spatial overlap. The beam energy is about 1 MeV and each electron pulse contains about 1



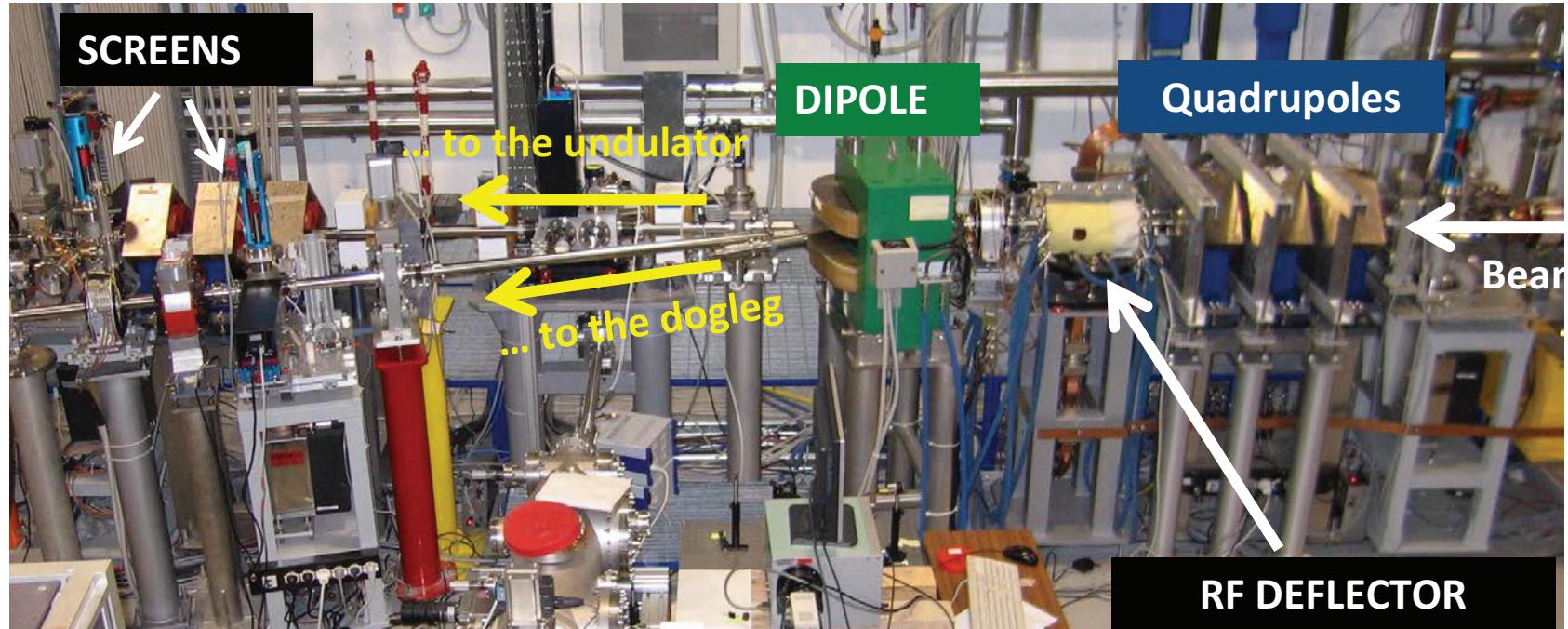
- ion phase of 35 deg and on the
- om the
- th achieved
- ecal energy
- sed.



- The phase of the third linac section is used to fine tune the central energy as well as the energy separation of the two pulses.
- By moving further S1 in the over-and moderate compression regime (typically 4-5 deg around -90°) one can obtain two pulses with tunable distance and energy separation.
- S2 and gun phases are slightly changed for improving the quality of the e-beam
- In order to precisely control the temporal distance between the two pulses and keep it constant over time, the RF phase jitter of the velocity bunching section must be reduced to less than 0.1 degrees (RMS) of RF phase. This was obtained using intrapulse RF feedback and a closed-loop circuit of the water temperature stabilization.

# The experiment: electron diagnostics

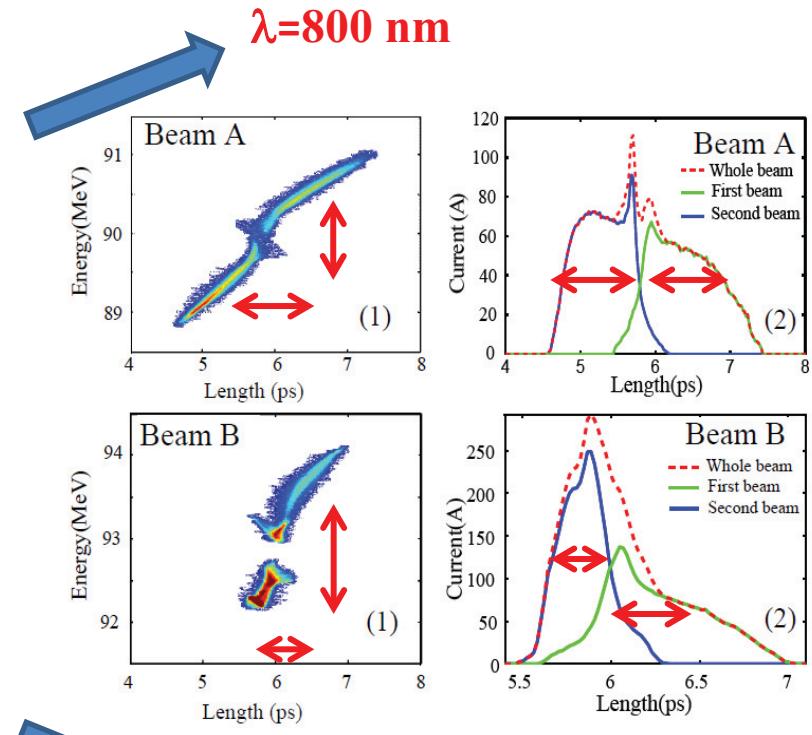
- the reconstruction of the longitudinal phase space is done with
  - vertical deflecting cavity coupled with
  - horizontally dispersing dipole(resolution of 50 fs in the bunch length measurements after deconvolution with the unstreaked spot size).
- Emittance measurements have been performed with the standard quadrupole scan technique at the linac exit



# The experiment: electron beam performances around the maximum compression

## Whole beam

	Beam A	Beam B
<b>Energy</b>	<b>90 MeV</b>	<b>93 MeV</b>
Charge	150 pC	160 pC
Current	120 A	300 A
Energy spread	0.6%	0.6%
Emittance	1.6 mm mrad	1.7 mm mrad
Duration	630 fs	300 fs



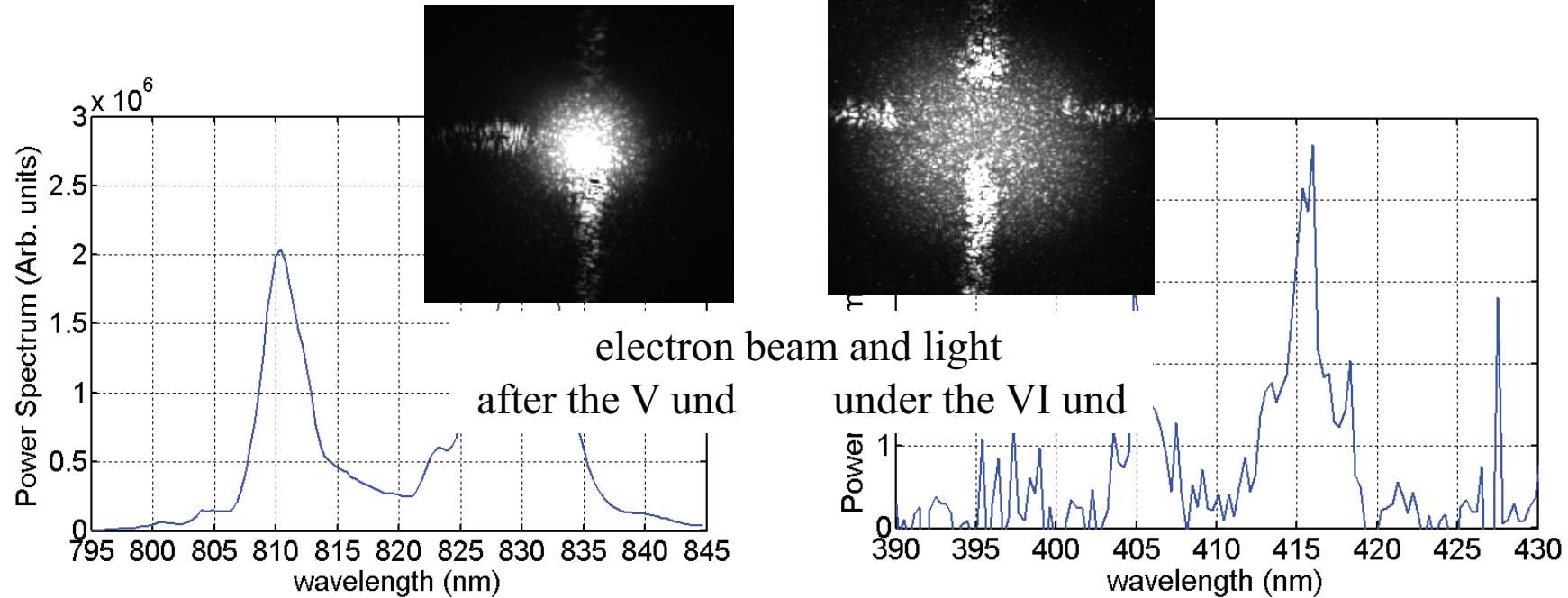
## Single bunch

<b>Energy separation</b>	<b>1.01 MeV</b>	<b>1.1 MeV</b>
<b>Time separation</b>	<b>0.7 ps</b>	<b>0.4 ps</b>
Energy spread	0.2%	0.3%
<b>Duration Dt</b>	<b>250-400 fs</b>	<b>100-250 fs</b>
<b><math>\rho</math></b>	<b><math>5 \cdot 10^{-4}</math></b>	<b><math>1.5 \cdot 10^{-3}</math></b>
<b>Cooperation length</b>	<b><math>36 \mu\text{m}</math></b>	<b><math>12.5 \mu\text{m}</math></b>

Overlapping of the beamlets

→  $\Delta E/E > 2\rho$  two independent beamlets  
 →  $Dt < 2\pi L_c/c$  single spike condition

# The experiment: matching to the undulator, alignment and FEL performance



- The total energy of both pulses is close to saturation. The measurements with the Joulemeter give always more than 40 microJ. Another indication of this is offered by the observation of the 2nd harmonic signal. Also the 2nd harmonic present a two peaked spectrum in good agreement with the predictions.

# The experiment: FEL photon diagnostics

## Fiber Spectrometer

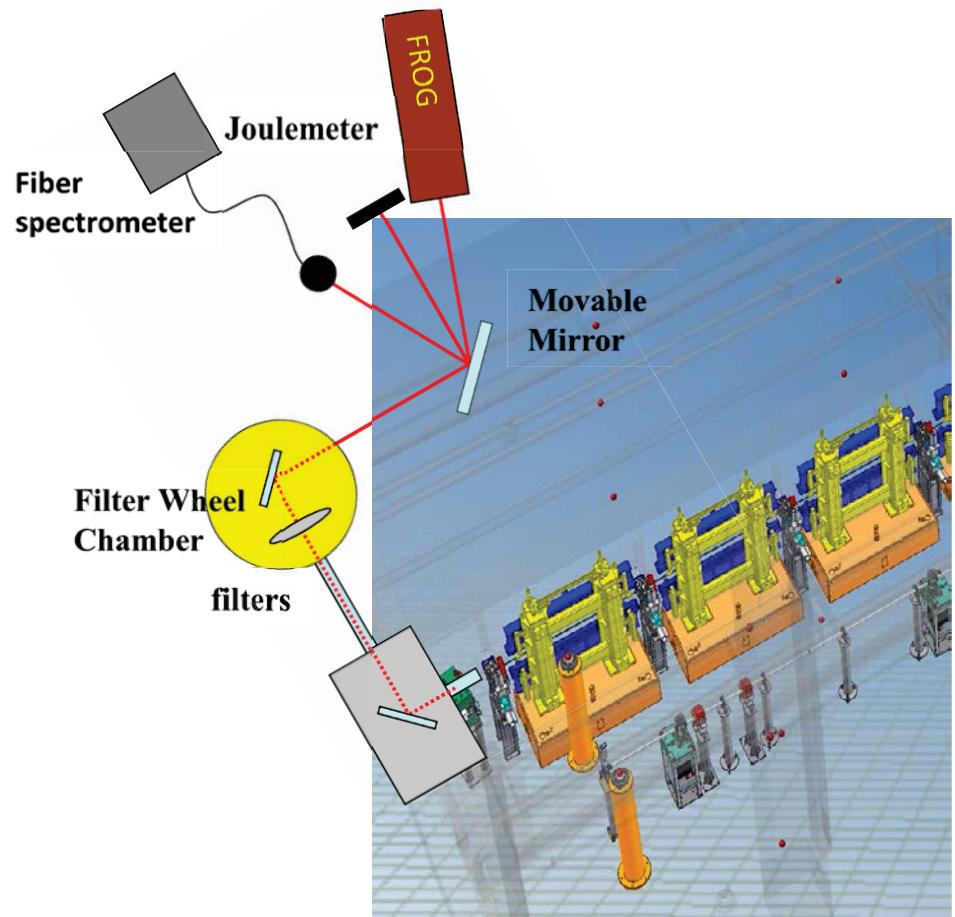
- Resolution: 1.2 nm @ 800 nm
- Window: 200-840 nm

## Joulemeter

- Minimum detected energy: 1 pJ
- Calibration:  $5.96e8 \text{ V/J}$  @  $1\mu\text{m}$
- Optical density filters

## FROG: NIR-Grenouille

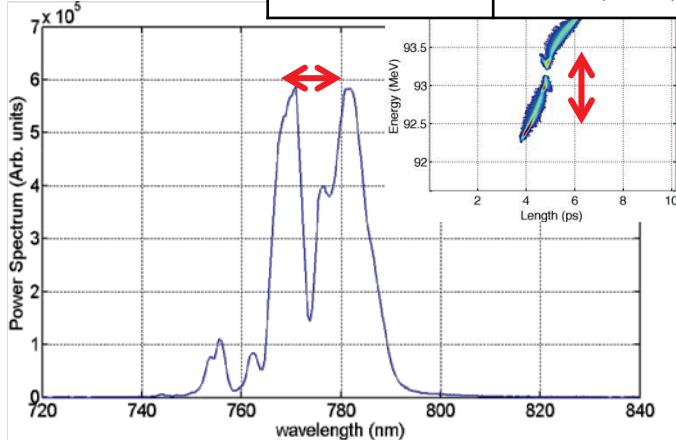
- Time-bandwidth product:  $\sim 10$
- Spectral resolution: 0.7 nm @800nm
- Single shot sensitivity: 1  $\mu\text{J}$



# The experiments: two-color radiation spectra

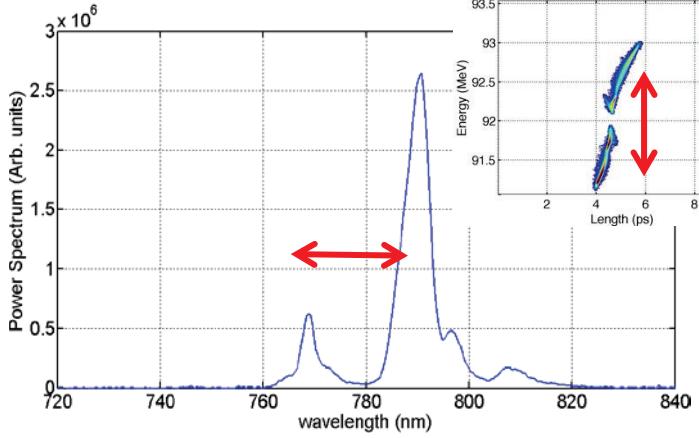
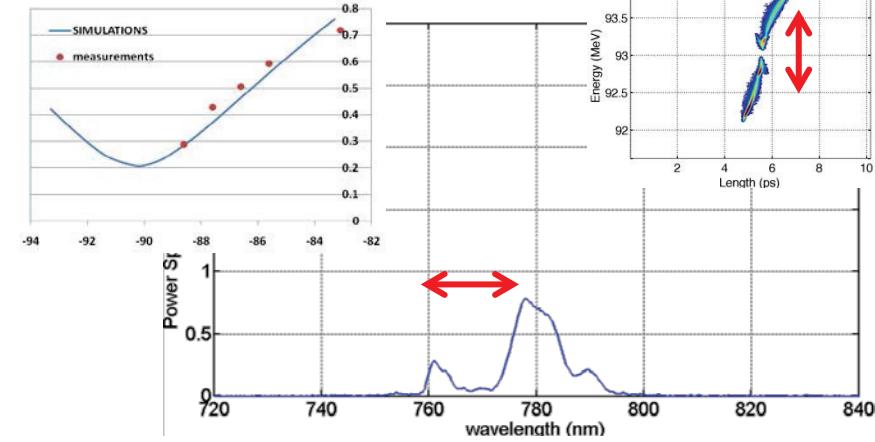
$\Delta\lambda=12 \text{ nm}$

S1 phase	-85.5
$\Delta E(\text{MeV})$	-0.92 (0.02)



$\Delta\lambda=18.8 \text{ nm}$

S1phase	-86.5
$\Delta E(\text{MeV})$	-0.97 (0.03)



$\Delta\lambda=21 \text{ nm}$

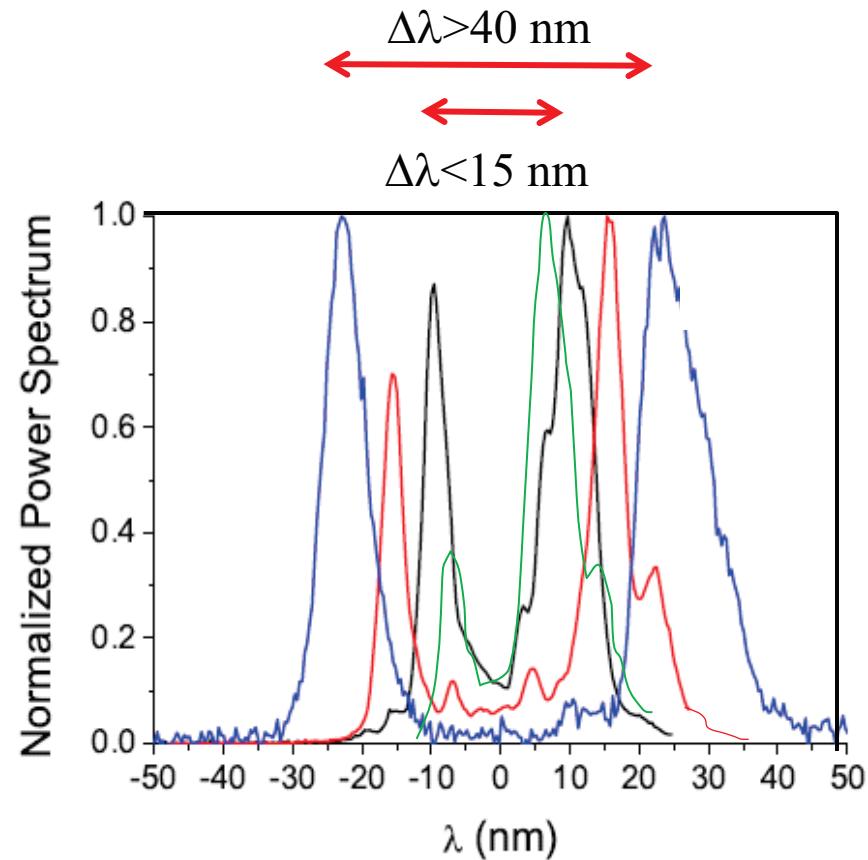
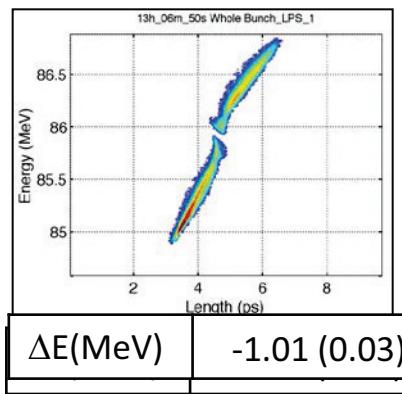
S1 phase	-87.5
$\Delta E(\text{MeV})$	-1.01 (0.03)

$\lambda_{\min} (\text{nm})$	773.8 (2)
$BW_{\lambda_{\min}} (\%)$	0.5
$\lambda_{\max} (\text{nm})$	800.6 (1.3)
$BW_{\lambda_{\max}} (\%)$	0.7
$\Delta\lambda (\text{nm})$	26 (2.9)
$\Delta E (\text{MeV})$	1.1 (0.17)
FEL Energy	> 37 $\mu\text{J}$

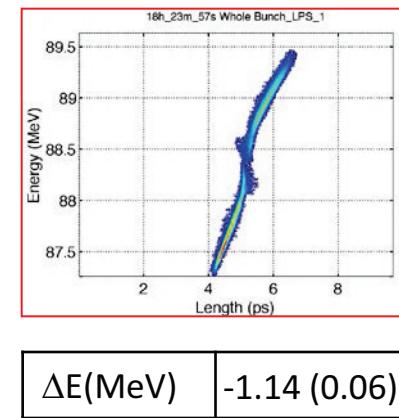
$\Delta\lambda=26 \text{ nm}$

S1 phase	-88.6
$\Delta E(\text{MeV})$	-1.14 (0.06)

# The experiment: Two-color tunability



$\Delta\lambda$ (nm)	20.7 (1.7)
$\Delta E$ (MeV)	1.066 (0.086)



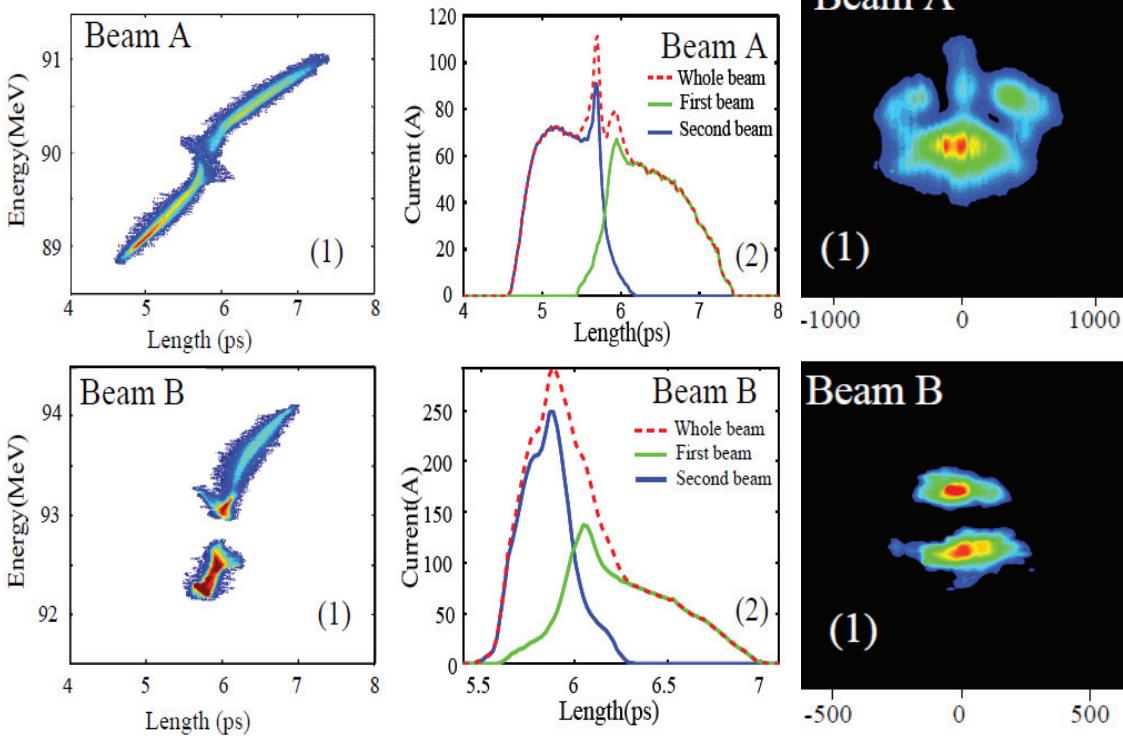
$\Delta\lambda$ (nm)	26 (3)
$\Delta E$ (MeV)	1.35 (0.14)

# The experiment: observation of multipeaked radiation

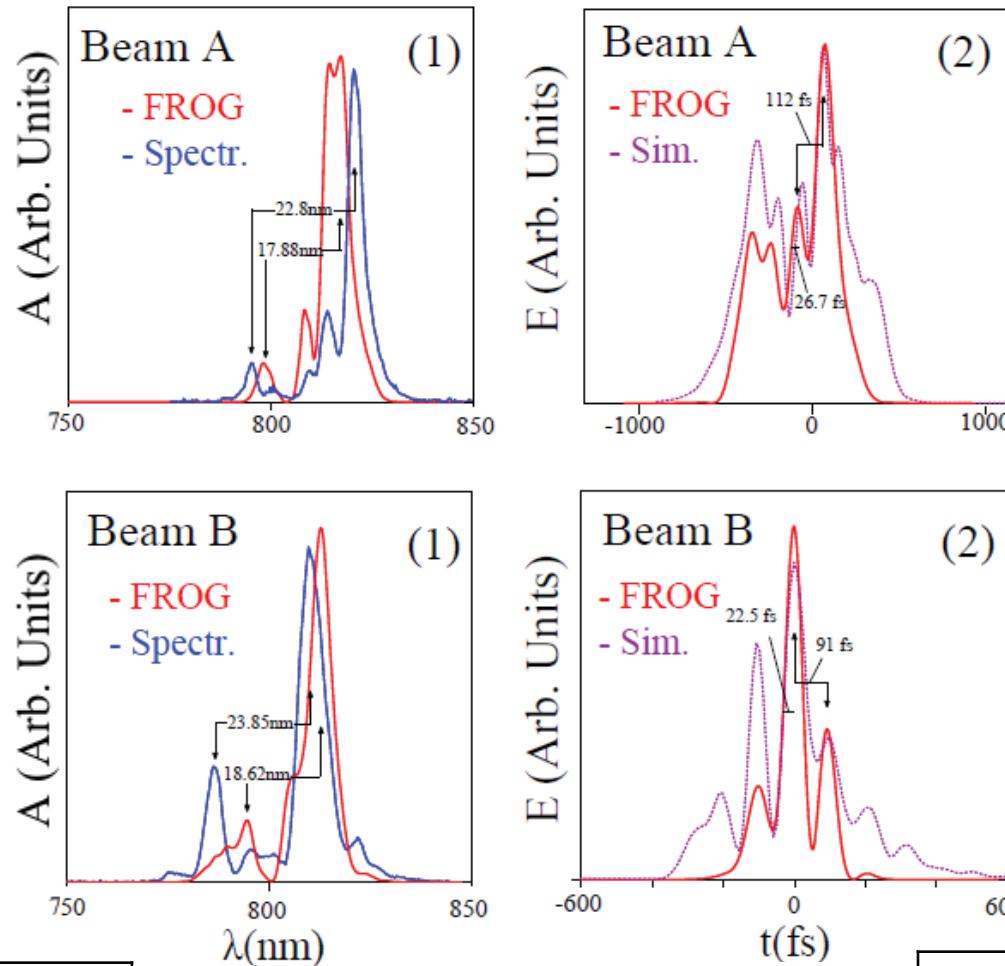
Beam	A	B
$\Delta\lambda$	22.8 nm	23.8 nm
$\Delta\lambda$ frog	17.9 nm	18.6 nm
$\Delta t$	112 fs	91 fs
$\sigma_t$	26.7 fs	22.5 fs

Frog Traces

Row data



# The experiment: production of multipeaked radiation



Beam	A	B
$\Delta\lambda$	22.8 nm	23.8 nm
$\Delta\lambda$ frog	17.9 nm	18.6 nm

Spectral domain

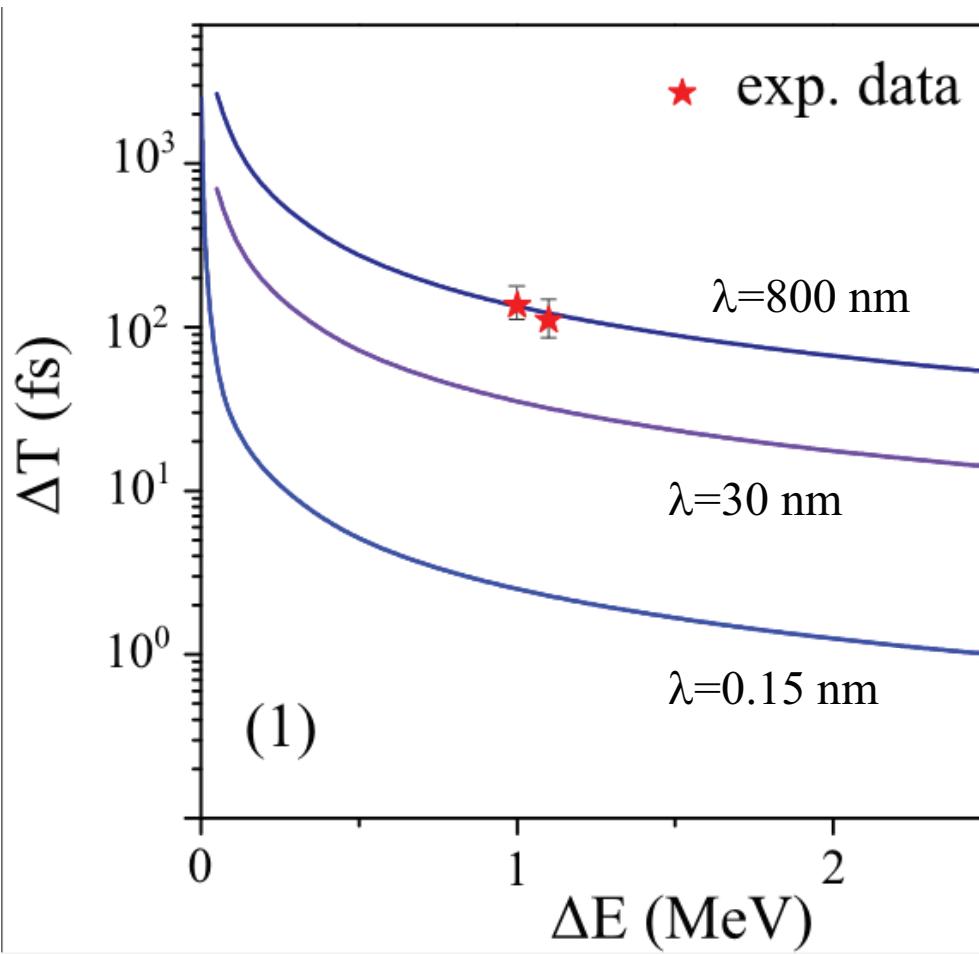
Time domain

Beam	A	B
$\Delta t$	112 fs	91 fs
$\sigma_t$	26.7 fs	22.5 fs

# The experiment: comparison with theory

Averaged values

Beam	$\Delta\lambda_{FR}(nm)$	$\Delta t_{rms}(fs)$	$V(%)$	$\Delta T(fs)$
A	$14 \pm 5$	$196 \pm 25$	35	$137 \pm 18$
B	$16.6 \pm 4.1$	$76.9 \pm 5.4$	85	$110 \pm 26$



# Conclusions

- Two-energy level electron beams produce two-color radiation and multipeaked pulses
- The method tested at SPARC is based on combed laser pulses, velocity bunching in the linac and single spike SASE emission by two independent beams
- The method permits a direct extrapolation to X rays and to shorter spatial structures
- Improvements in coherence can be obtained by seeding the radiation with large spectrum laser
- The use of the two-level electron beam in the SPARC Thomson source could produce two color X-rays

