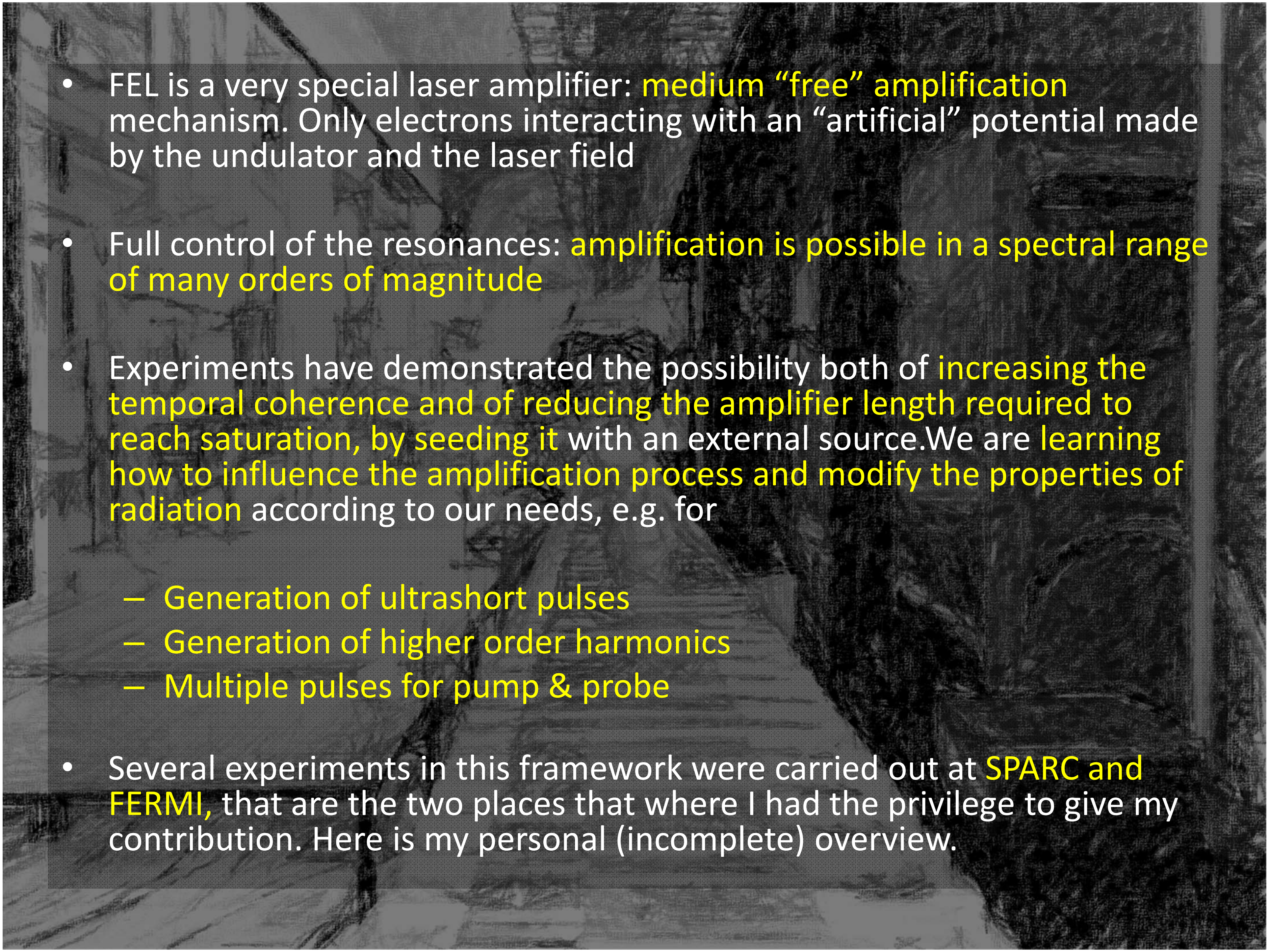
Pulse Control in a Free Electron Laser Amplifier

Luca Giannessi

ENEA C.R. Frascati & Elettra-Sincrotrone Trieste

FEL 2014 Basel

2014 International FEL conference - Basel, August 25 2014



- FEL is a very special laser amplifier: medium “free” amplification mechanism. Only electrons interacting with an “artificial” potential made by the undulator and the laser field

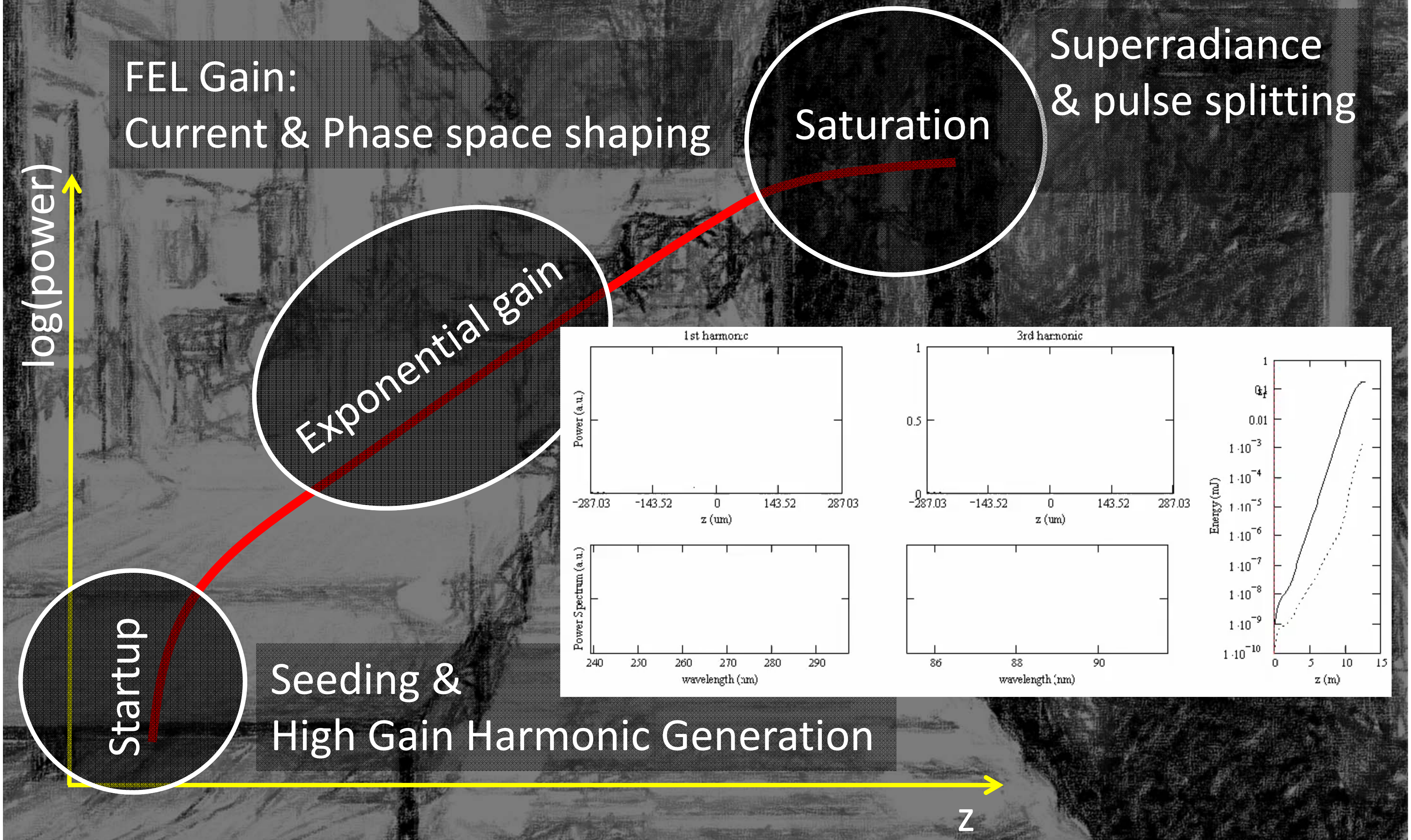
- Full control of the resonances: amplification is possible in a spectral range of many orders of magnitude

- Experiments have demonstrated the possibility both of increasing the temporal coherence and of reducing the amplifier length required to reach saturation, by seeding it with an external source.We are learning how to influence the amplification process and modify the properties of radiation according to our needs, e.g. for

  - Generation of ultrashort pulses
  - Generation of higher order harmonics
  - Multiple pulses for pump & probe

- Several experiments in this framework were carried out at SPARC and FERMI, that are the two places that where I had the privilege to give my contribution. Here is my personal (incomplete) overview.

Power growth in a high gain FEL amplifier



FEL Gain:
Current & Phase space shaping

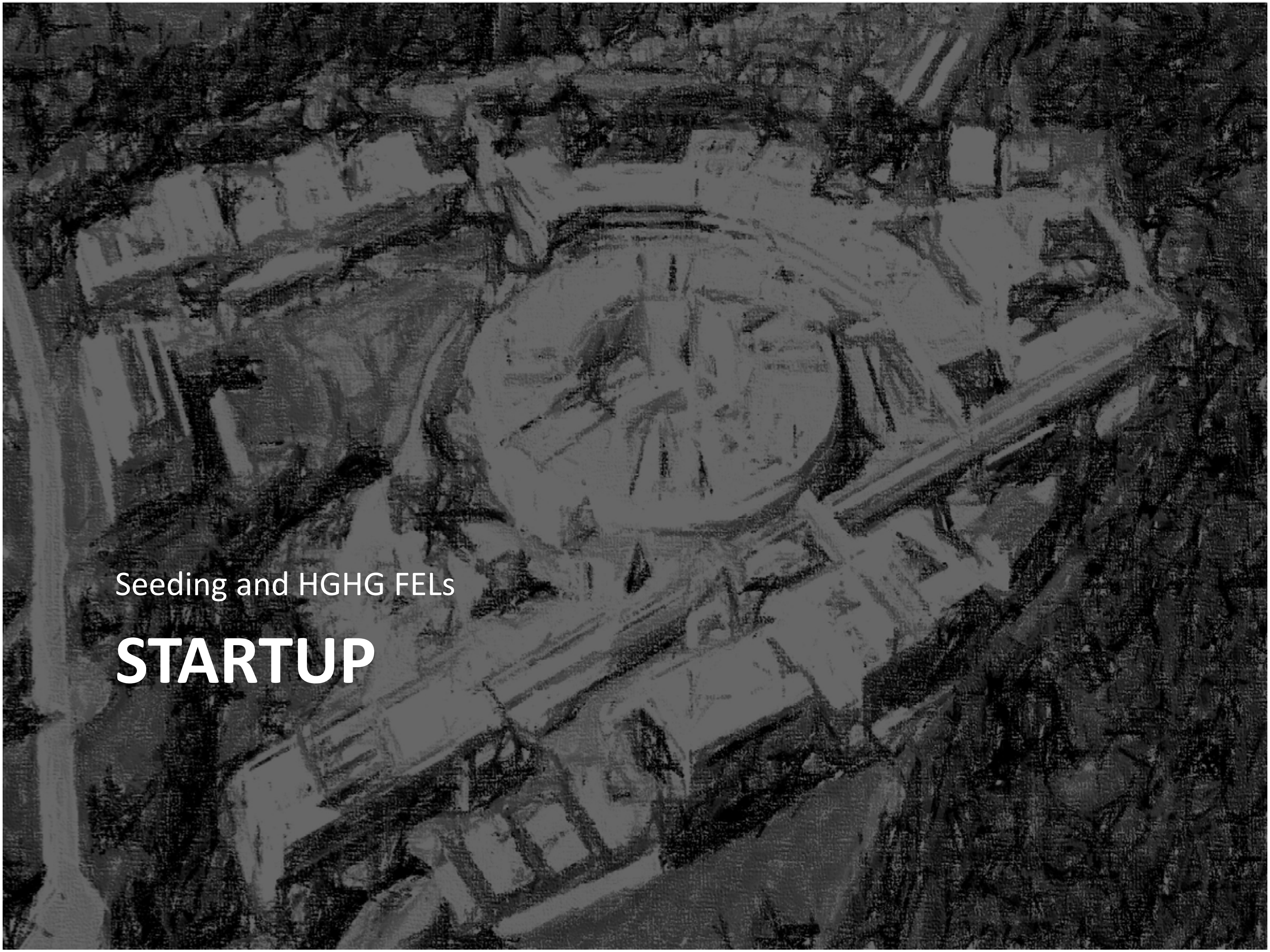
Saturation

Superradiance
& pulse splitting

Exponential gain

Startup

Seeding &
High Gain Harmonic Generation



Seeding and HGHG FELs

STARTUP

Startup – Seeded FEL amplifier

FEL integral equation starting from a pre-modulated beam*

$$\frac{d}{d\tau}a(\tau) = -2\pi g_0 b_1 e^{-i\nu_0\tau} - i\pi g_0 b_2 e^{-2i\nu_0\tau}\int_0^\tau d\xi\xi e^{i\nu_0\xi}a^*(\tau-\xi) + i\pi g_0\int_0^\tau d\xi\xi e^{-i\nu_0\xi}a(\tau-\xi)$$

Shot noise, spontaneous emission (or emission from a pre bunched beam)

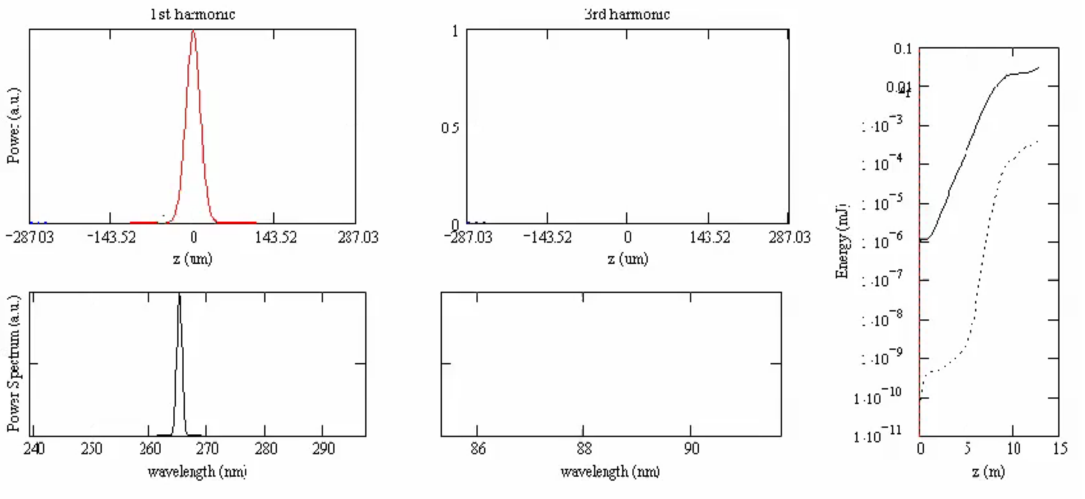
Negligible at startup (prop. to field a & b_2)

High gain growing roots

Comparing the first and third term we find an intensity level corresponding to e-shot noise

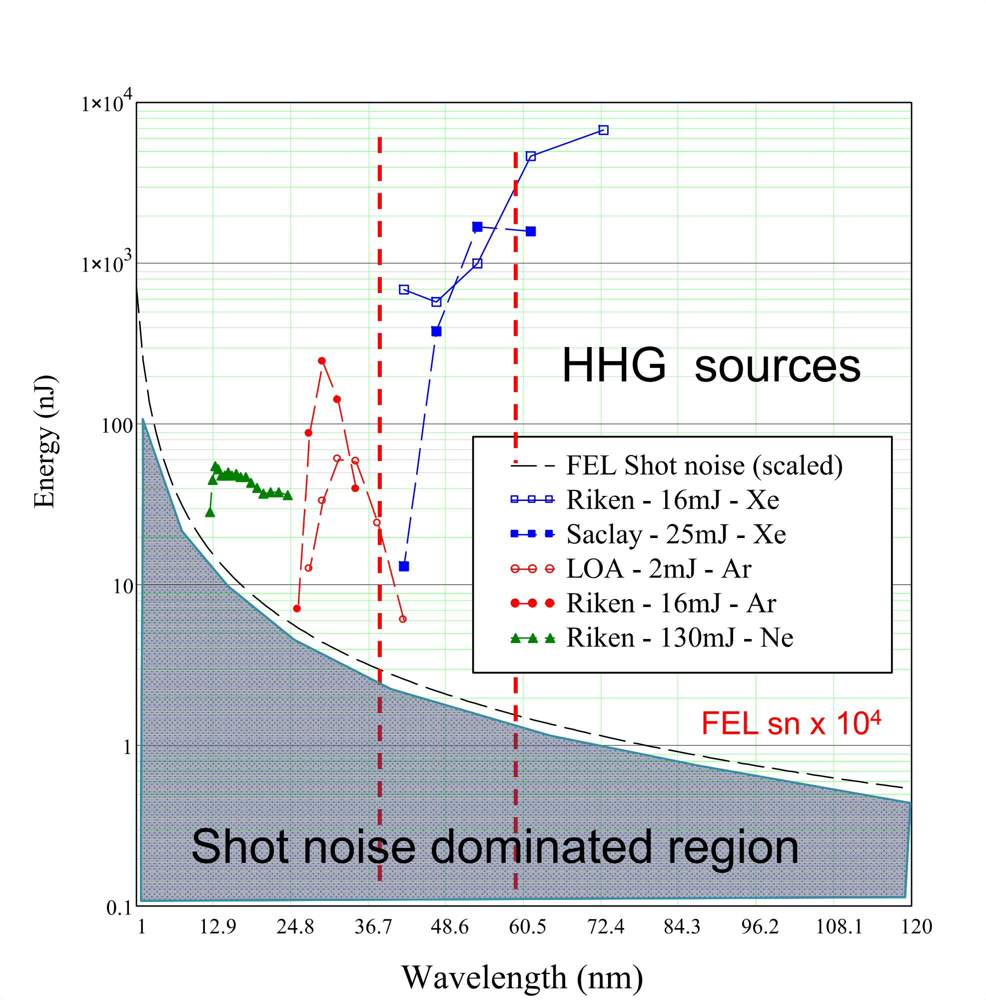
$$I_{sn} \approx 3\,\omega\,\gamma m_0 c^2 \rho_{fel}^2$$

ω resonant frequency
$\gamma m_0 c^2$ e-beam energy
ρ_{fel} FEL parameter

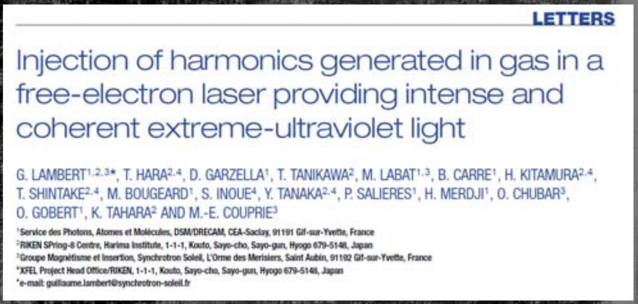


*G. Dattoli et al. Phys. Rev. E 49 (1994) a, ξ, v coortinates in Colson's notation, b_1,b_2 1st & 2nd bunching coeffs

Direct seeding an amplifier: the seed power required to overcome the shot noise scale with the inverse of the wavelength



SCSS (2008) 160nm



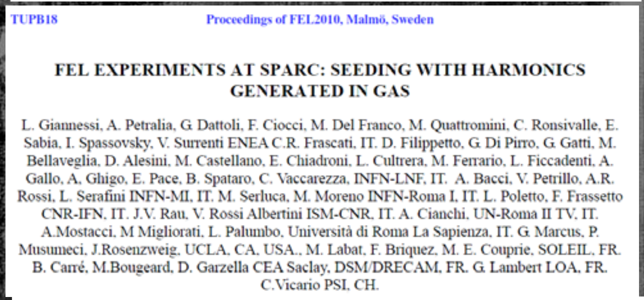
LETTERS

Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light

G. LAMBERT[1,2,3*], T. HARA[2,4], D. GARZELLA[1], T. TANIKAWA[2], M. LABAT[1,3], B. CARRE[1], H. KITAMURA[2,4], T. SHINTAKE[2,4], M. BOUGEARD[1], S. INOUE[4], Y. TANAKA[2,4], P. SALIERES[1], H. MERDJI[1], O. CHUBAR[3], O. GOBERT[1], K. TAHARA[2] AND M.-E. COUPRIE[3]

[1] Service des Photons, Atomes et Molécules, DSM/DRECAM, CEA-Saclay, 91191 Gif-sur-Yvette, France
[2] RIKEN SPring-8 Centre, Harima Institute, 1-1-1, Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan
[3] Groupe Magnétisme et Insertion, Synchrotron Soleil, L'Orme des Merisiers, Saint Aubin, 91192 Gif-sur-Yvette, France
[4] XFEL Project Head Office/RIKEN, 1-1-1, Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan
*e-mail: guillaume.lambert@synchrotron-soleil.fr

SPARC (2010) 160nm

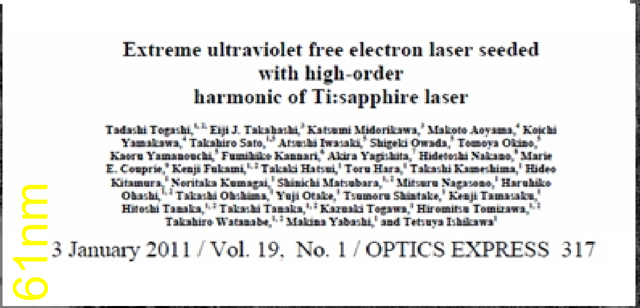


TUPB18 Proceedings of FEL2010, Malmö, Sweden

FEL EXPERIMENTS AT SPARC: SEEDING WITH HARMONICS GENERATED IN GAS

L. Giannessi, A. Petralia, G Dattoli, F. Ciocci, M. Del Franco, M. Quattromini, C. Ronsivalle, E. Sabia, I. Spassovsky, V. Surrenti ENEA C.R. Frascati, IT. D. Filippetto, G Di Pirro, G Gatti, M. Bellaveglia, D. Alesini, M. Castellano, E. Chiadroni, L. Cultrera, M. Ferrario, L. Ficcadenti, A. Gallo, A. Ghigo, E. Pace, B. Spataro, C. Vaccarezza, INFN-LNF, IT. A. Bacci, V. Petrillo, A.R. Rossi, L. Serafini INFN-MI, IT. M. Serluca, M. Moreno INFN-Roma I, IT. L. Poletto, F. Frassetto CNR-IFN, IT. J.V. Rau, V. Rossi Albertini ISM-CNR, IT. A. Cianchi, UN-Roma II TV, IT. A.Mostacci, M Migliorati, L. Palumbo, Università di Roma La Sapienza, IT. G Marcus, P. Musumeci, J.Rosenzweig, UCLA, CA, USA., M. Labat, F. Briquez, M. E. Couprie, SOLEIL, FR. B. Carré, M.Bougeard, D. Garzella CEA Saclay, DSM/DRECAM, FR. G Lambert LOA, FR. C.Vicario PSI, CH.

SCSS (2011) 61nm

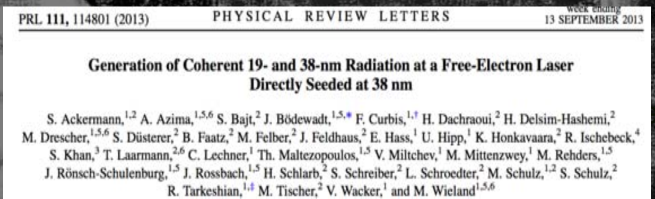


Extreme ultraviolet free electron laser seeded with high-order harmonic of Ti:sapphire laser

Tadashi Togashi,[1,2] Eiji J. Takahashi,[3] Katsumi Midorikawa,[3] Makoto Aoyama,[4] Koichi Yamakawa,[4] Takahiro Sato,[1,3] Atsushi Iwasaki,[5] Shigeki Owada,[5] Tomoya Okino,[5] Kaoru Yamanouchi,[5] Fumihiko Kannari,[6] Akira Yagishita,[7] Hidetoshi Nakano,[8] Marie E. Couprie,[9] Kenji Fukami,[1,2] Takaki Hatsui,[1] Toru Hara,[1] Takashi Kameshima,[1] Hideo Kitamura,[1] Noritaka Kumagai,[1] Shinichi Matsubara,[1,2] Mitsuru Nagasono,[1] Haruhiko Ohashi,[1,2] Takashi Ohshima,[1] Yuji Otake,[1] Tsumoru Shintake,[1] Kenji Tamasaku,[1] Hitoshi Tanaka,[1,2] Takashi Tanaka,[1,2] Kazuaki Togawa,[1] Hiromitsu Tomizawa,[1,2] Takahiro Watanabe,[1,2] Makina Yabashi,[1] and Tetsuya Ishikawa[1]

3 January 2011 / Vol. 19, No. 1 / OPTICS EXPRESS 317

DESY (2012) 38nm



PRL **111,** 114801 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

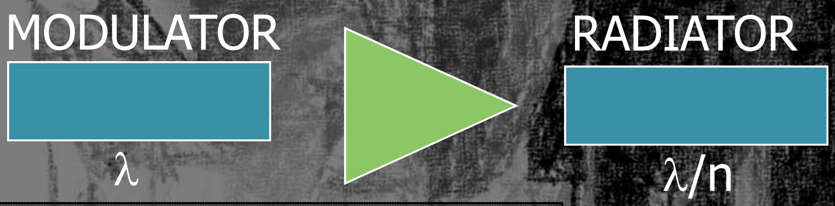
Generation of Coherent 19- and 38-nm Radiation at a Free-Electron Laser Directly Seeded at 38 nm

S. Ackermann,[1,2] A. Azima,[1,5,6] S. Bajt,[2] J. Bödewadt,[1,5,*] F. Curbis,[1,†] H. Dachraoui,[2] H. Delsim-Hashemi,[2] M. Drescher,[1,5,6] S. Düsterer,[2] B. Faatz,[2] M. Felber,[2] J. Feldhaus,[2] E. Hass,[1] U. Hipp,[1] K. Honkavaara,[2] R. Ischebeck,[4] S. Khan,[3] T. Laarmann,[2,6] C. Lechner,[1] Th. Maltezopoulos,[1,5] V. Miltchev,[1] M. Mittenzwey,[1] M. Rehders,[1,5] J. Rönsch-Schulenburg,[1,5] J. Rossbach,[1,5] H. Schlarb,[2] S. Schreiber,[2] L. Schroedter,[2] M. Schulz,[1,2] S. Schulz,[2] R. Tarkeshian,[1,‡] M. Tischer,[2] V. Wacker,[1] and M. Wieland[1,5,6]

- *data from B. Carré, Colloque AEC - Slicing, Paris 2004*
- *Estimate includes transport and matching to e-beam – Seeded FELs Workshop, Frascati 10-12 (2008)*

The FEL as an “harmonic converter”

I.Boscolo, V. Stagno, Il Nuovo Cimento 58, 271 (1980)



- *R. Barbini et al. Procs “Prospects for a 1 A FEL, Sag Harbor, New York April 22-27, 1990 BNL 52273 UC-414*
(1990)
- *R. Bonifacio et*
- *L. H. Yu PRA 4*
- *F. Ciocci et al.*

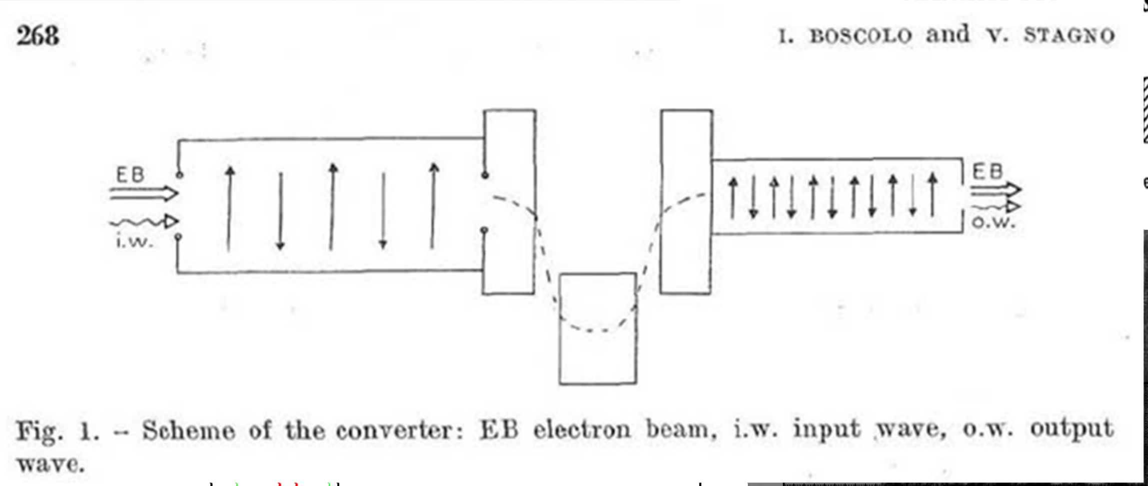
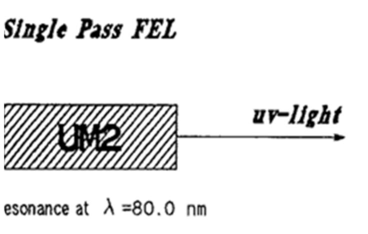
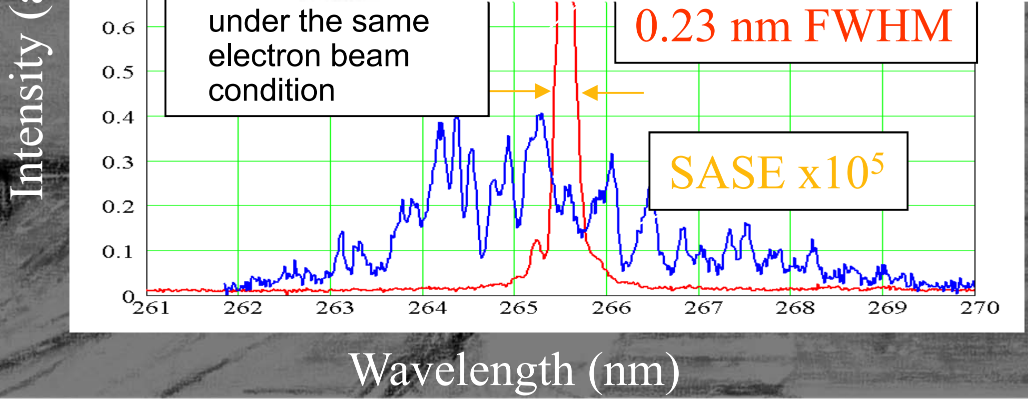

268 I. BOSCOLO and V. STAGNO

Fig. 1. – Scheme of the converter: EB electron beam, i.w. input wave, o.w. output wave.





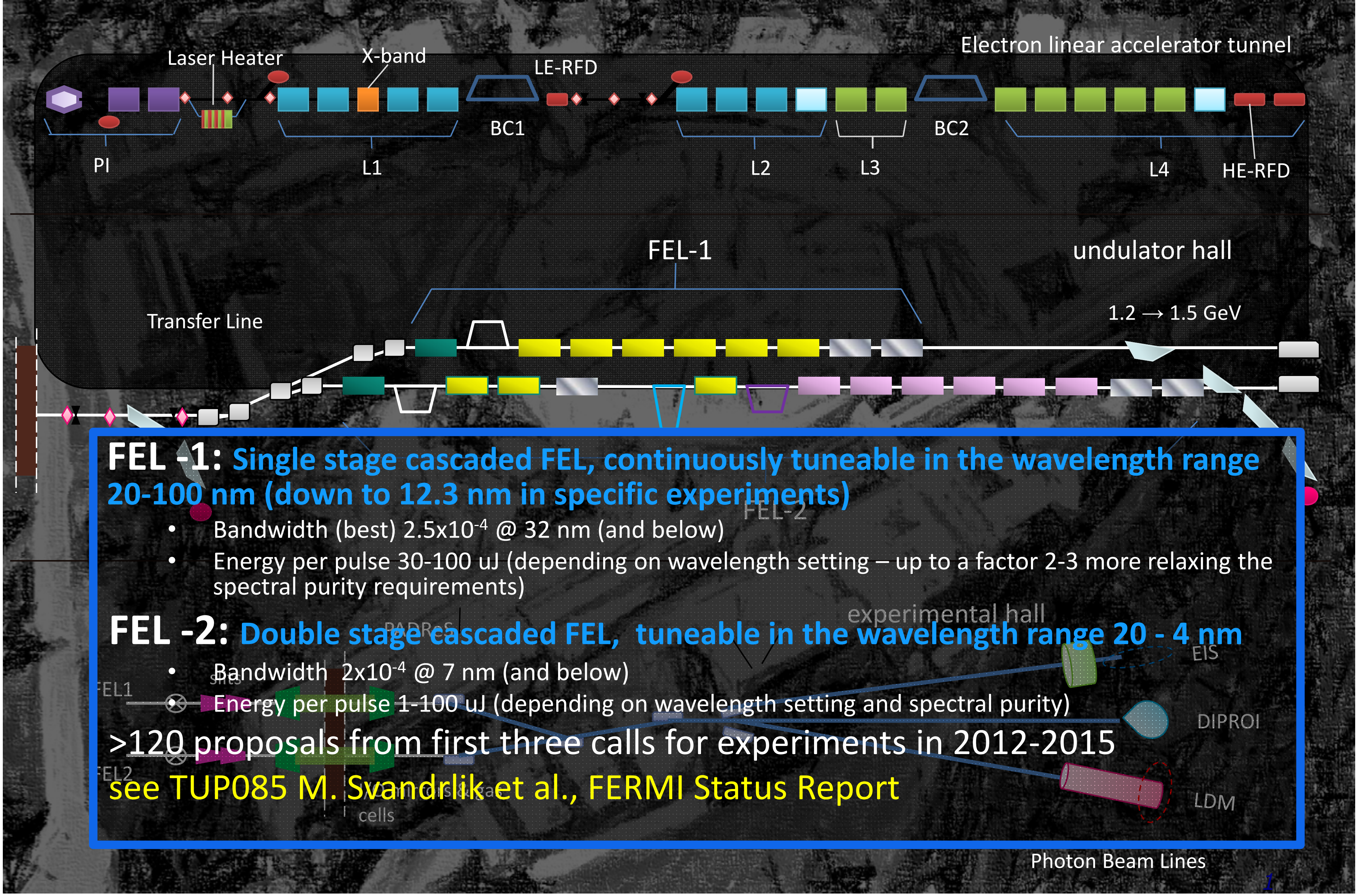
HGHG Experiment

L. H. Yu et al. Science 289 (2000)

UV HGHG Experiment

L. H. Yu et al. PRL 91 (2003)

FERMI FEL Facility: FEL-1 and FEL-2



FEL -1: **Single stage cascaded FEL, continuously tuneable in the wavelength range 20-100 nm (down to 12.3 nm in specific experiments)**

- Bandwidth (best) 2.5x10^{-4} @ 32 nm (and below)
- Energy per pulse 30-100 uJ (depending on wavelength setting – up to a factor 2-3 more relaxing the spectral purity requirements)

FEL -2: **Double stage cascaded FEL, tuneable in the wavelength range 20 - 4 nm**

- Bandwidth 2x10^{-4} @ 7 nm (and below)
- Energy per pulse 1-100 uJ (depending on wavelength setting and spectral purity)

>120 proposals from first three calls for experiments in 2012-2015

see TUP085 M. Svandrlik et al., FERMI Status Report

FERMI FEL-1: nominal range 100 – 20nm

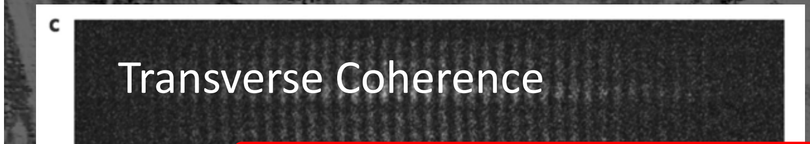
nature photonics

ARTICLES

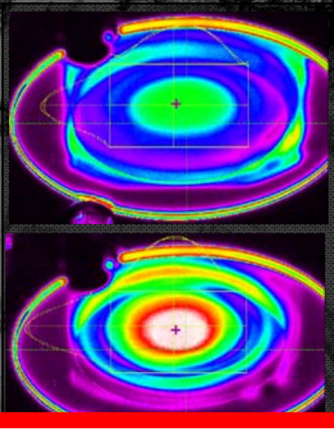
PUBLISHED ONLINE: 23 SEPTEMBER 2012 | DOI: 10.1038/NPHOTON.2012.233

Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet

E. Allaria *et al.**



Transverse Coherence

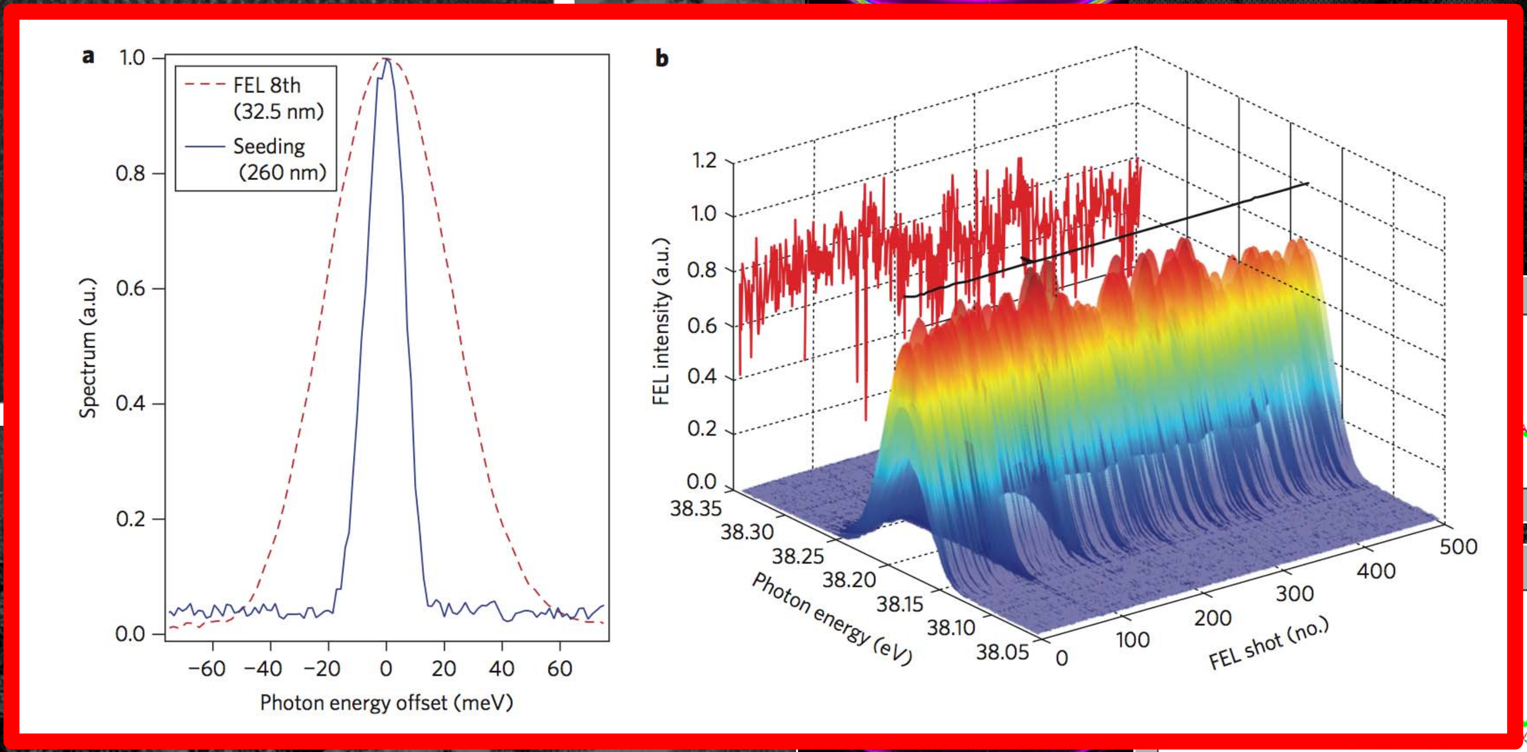


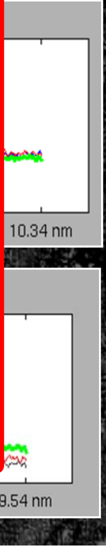
@ 52 nm (h5)

2200s Mean 320 µJ

@ 26 nm (h10)

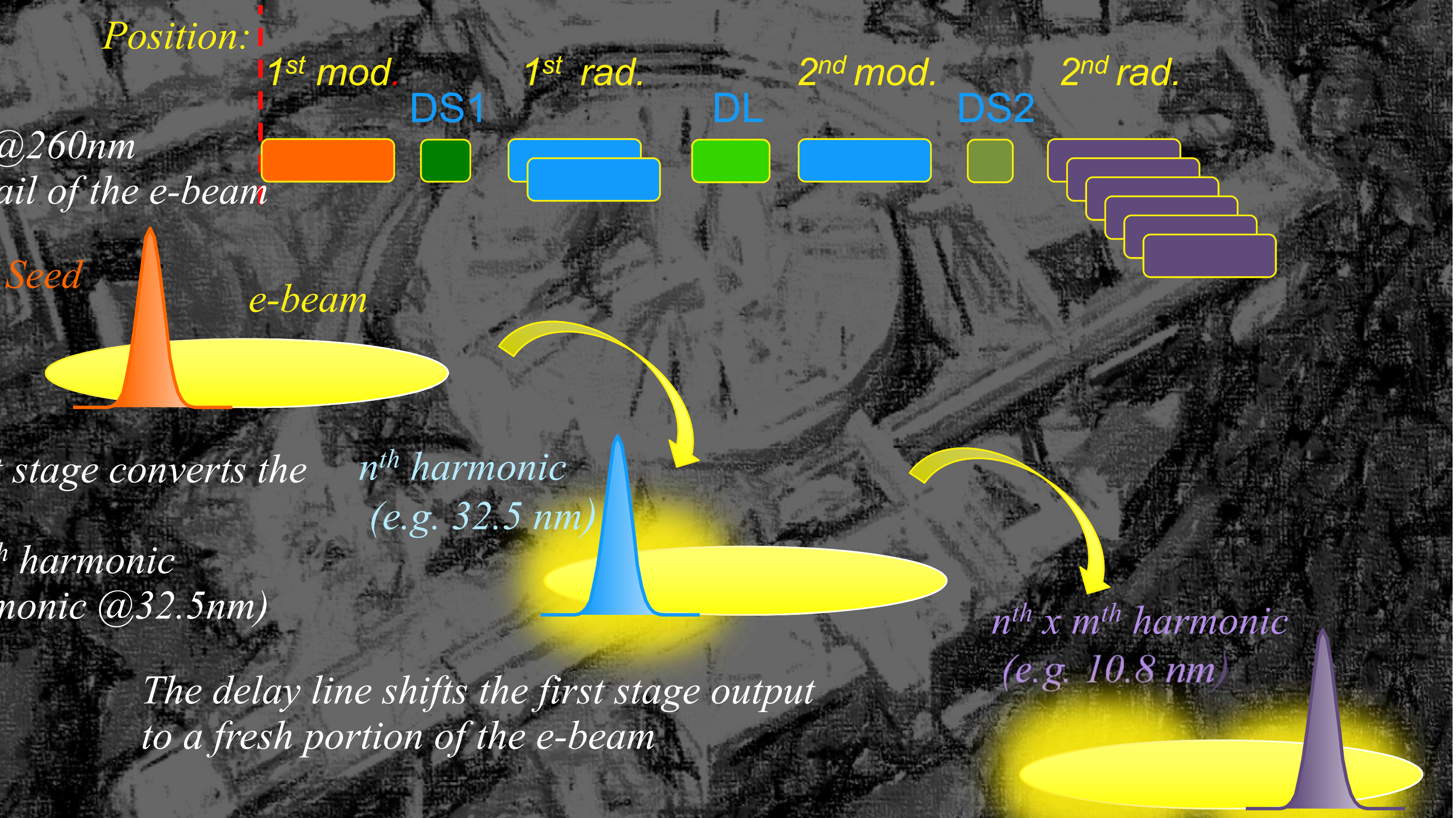
≈ 250 µJ





Elettra

FERMI FEL-2: The Fresh Bunch Injection Technique*



The seed @260nm is on the tail of the e-beam

The first stage converts the seed to the nth harmonic (8^{th} harmonic @32.5nm)

The delay line shifts the first stage output to a fresh portion of the e-beam

The second stage converts the first stage to the n^{th} x m^{th} harmonic of the seed

*L. H. Yu, I. Ben-Zvi, Nim 1993

FEL-2 brief history

- **Run 13** (September 2012) 1.0 GeV
  - FIRST LASING @ 14.4 & 10.8 nm

Run 15 (March 2013) 1.25 GeV

8.1 & 6.5 nm

test of BC1+BC2 compression

Run 16 (June 2013) 1.45 GeV

6.5 nm -> 4 nm

BC1, BC2 & Ramped PI Laser Shape

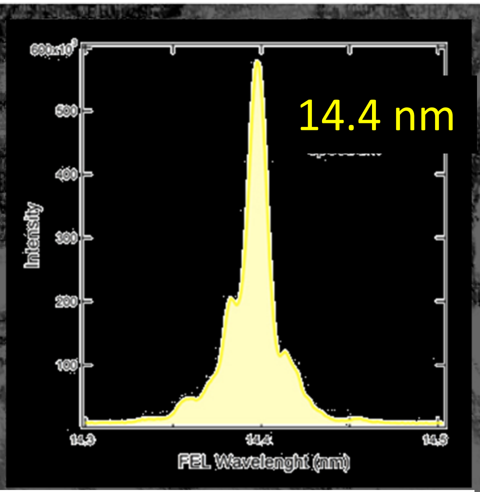
Run 17 (September 2013) 1.25 GeV

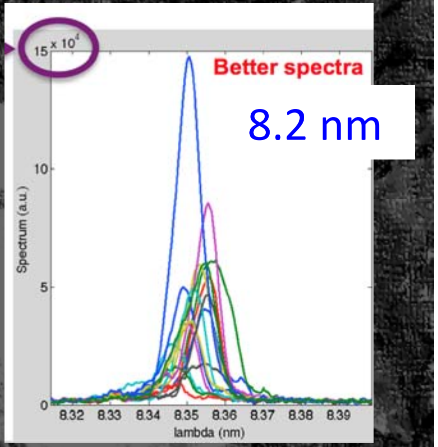
Increase energy & stability @7.5 nm

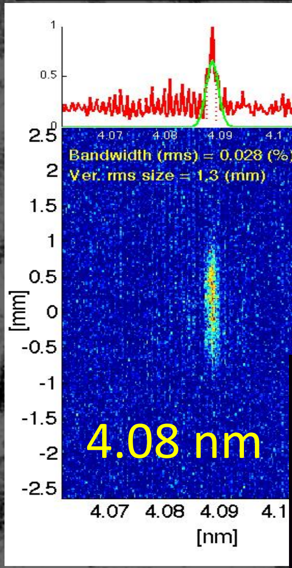
BC1 Tested higher compression factors

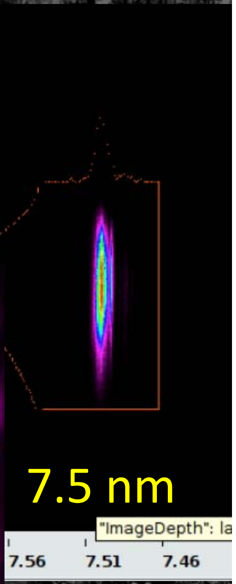
Run 20 (May-June2014) 1.5 GeV

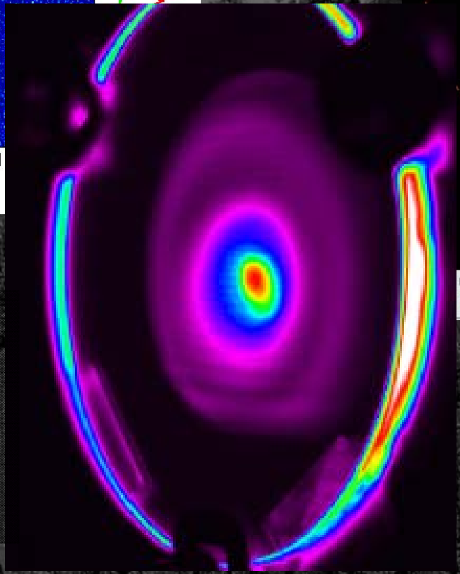
Increased energy & stability @4nm (10 uJ)
Measured higher order harmonics









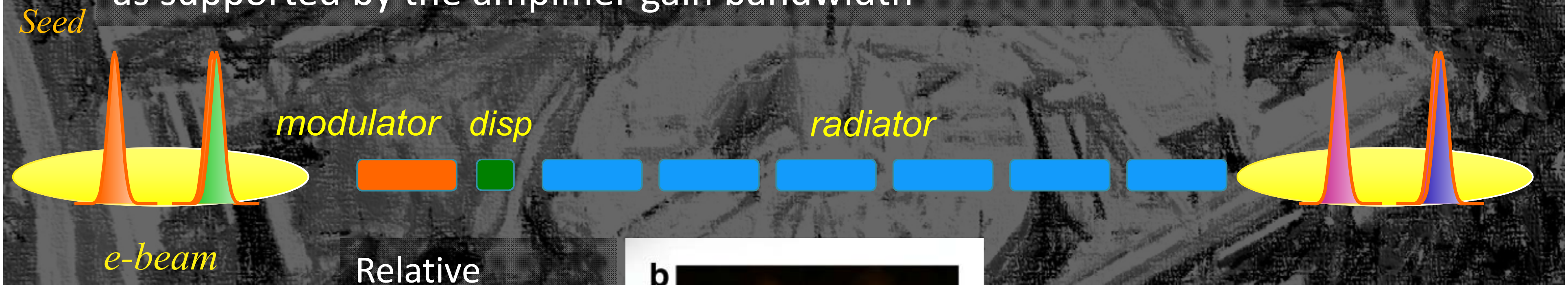


Yag screen with 1^{st} and 2^{nd} stage spots

FEL-1: Two Color Pump-probe experiments

E. Allaria et al. Nat. Comm. 4:2476 DOI: 10.1038/ncomms3476

The FEL can be seeded with two pulses, even separated in frequency, so long as supported by the amplifier gain bandwidth

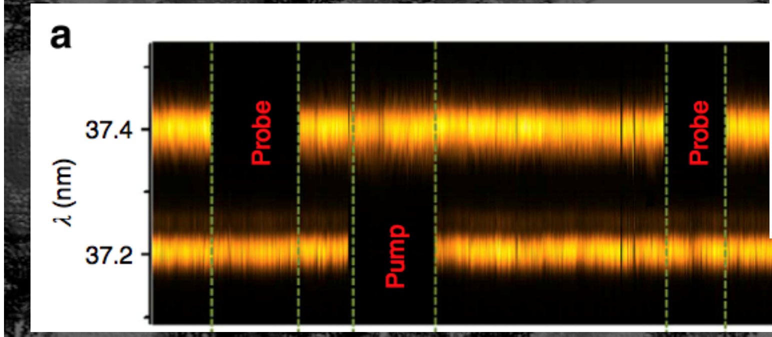


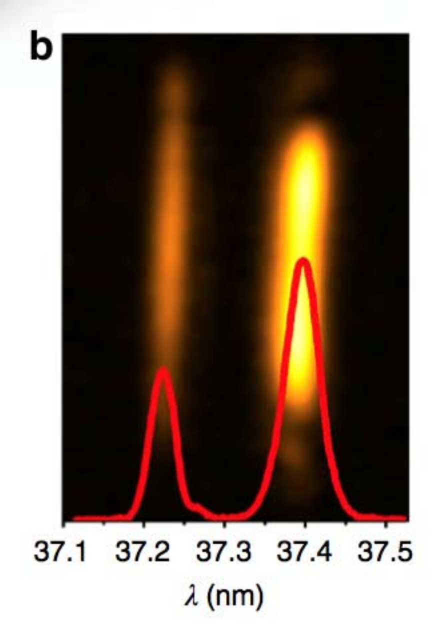
Full control of:

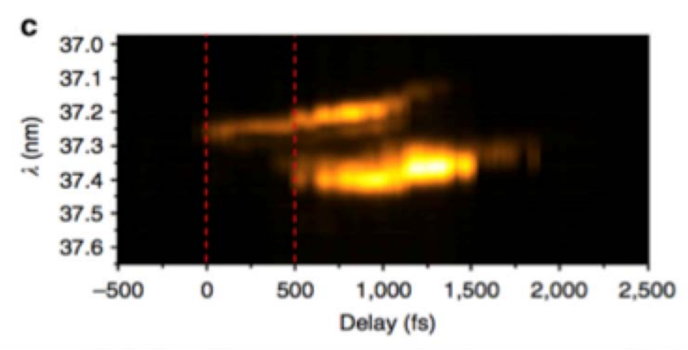
Relative amplitudes, via undulator resonance/seed

pump/probe on-off

Temporal/spectral separation, via seed laser



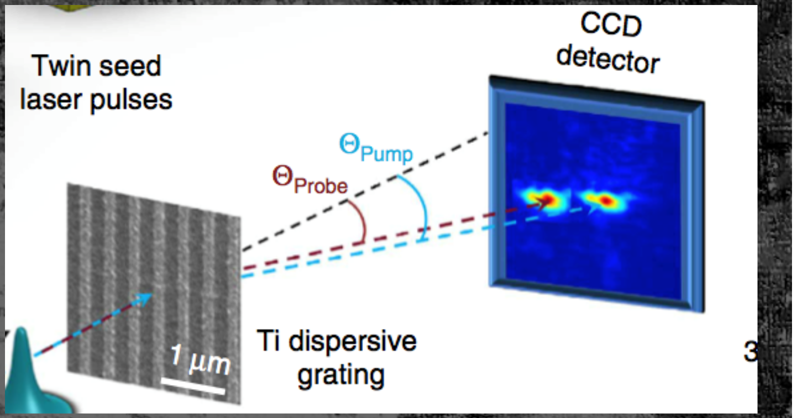




DIPROI

coord. M. Kiskinova, beamline responsible F. Capotondi

E. Allaria et al. Nat. Comm. 4:2476 DOI: 10.1038/ncomms3476

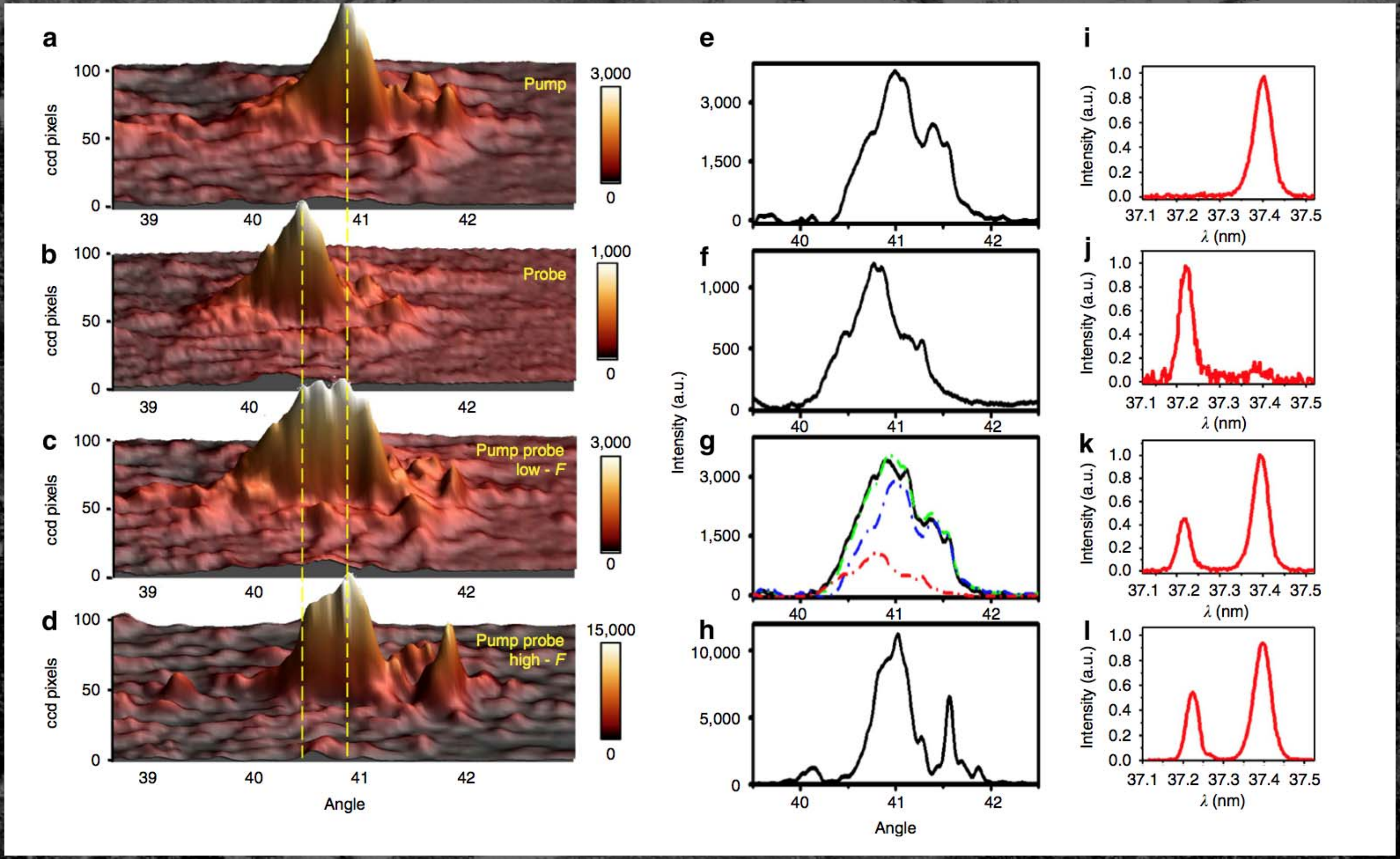


PUMP

PROBE

PUMP + PROBE

HIGH FLUX PUMP + PROBE



Single spike, comb structures and chirped pulse amplification

GAIN “SHAPING”

Single spike amplification

A simple example of gain shaping consist in limiting the bunch capability of lasing, by spoiling the bunch properties where lasing is not desired

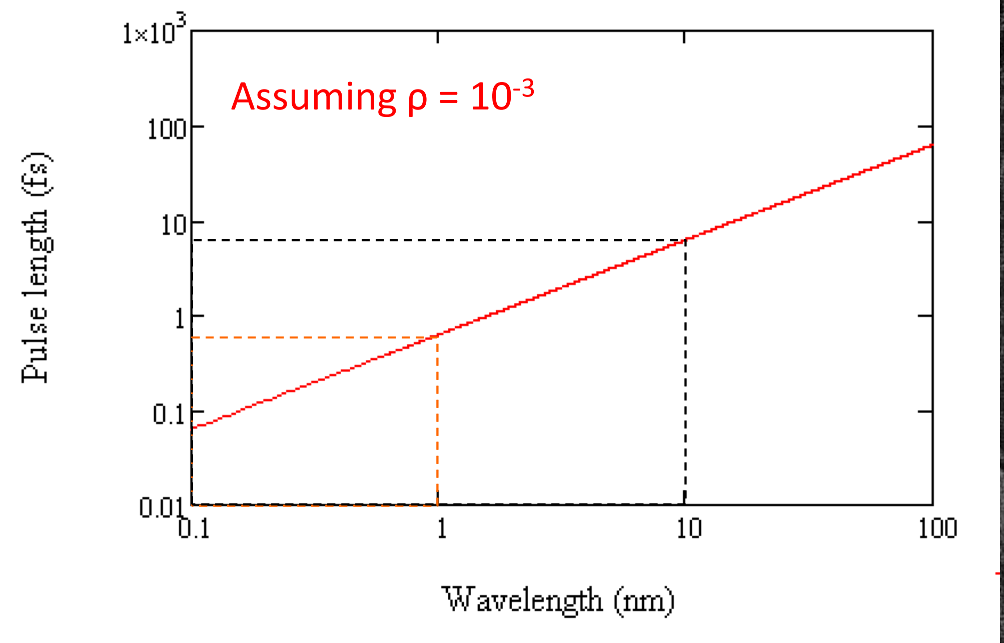
P. Emma et al. Phys. Rev. Lett. 92, 074801 (2004)

Y. Ding et al., Phys. Rev. Lett. 109, 254802 (2012)

Or by compressing the bunch to a length (≈2π) shorter than the FEL cooperation length

$$l_c = \frac{\lambda_0}{4\pi\rho}$$

J. Rosenzweig et al. NIM A593, 39 (2008)

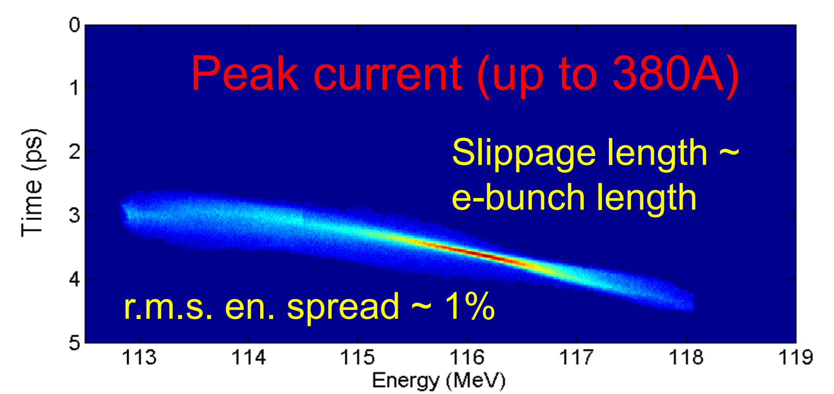


An FEL amplifier with $\rho \approx 10^{-3}$ has sufficent bandwidth to support sub-fs (fwhm) pulses below 1 nm and sub-10 fs below 10 nm.

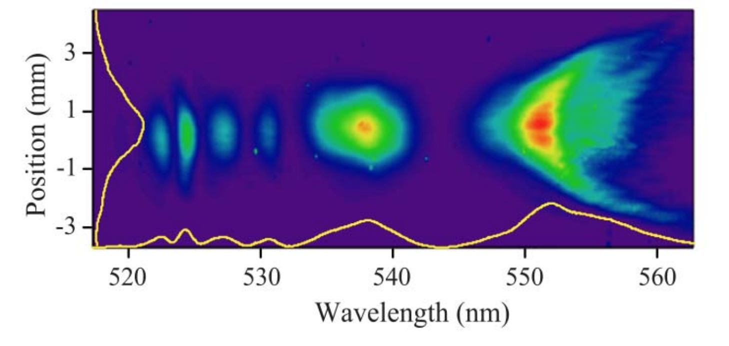
Scaled experiment for single spike generation: SASE with chirped & compressed beam

L. Giannessi et al. PRL 106, 144801 (2011)

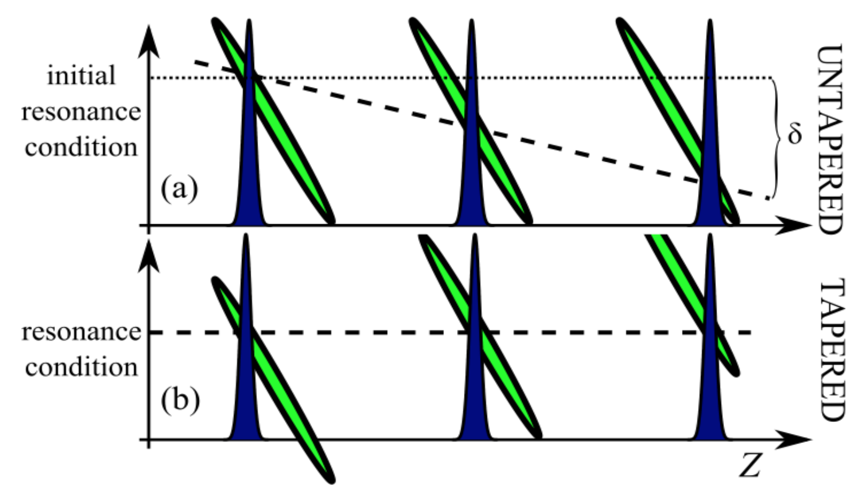
Compression with "Velocity Bunching" strong chirp & energy spread in the longitudinal phase space

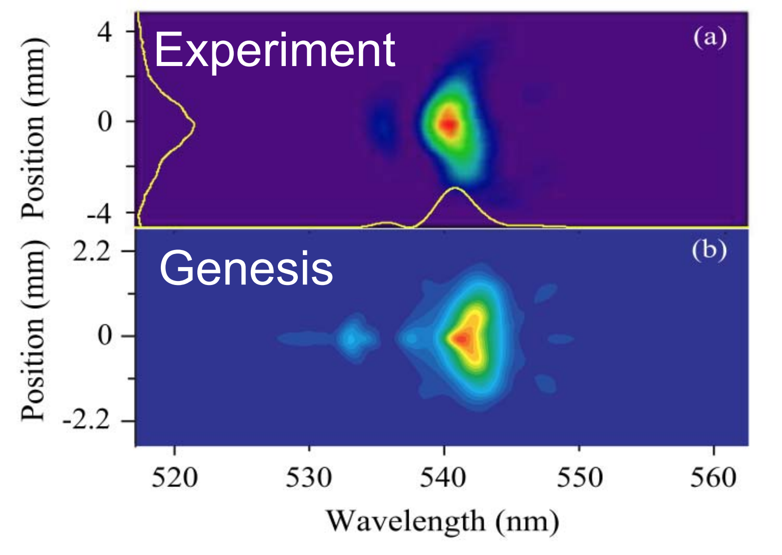


Spectrum



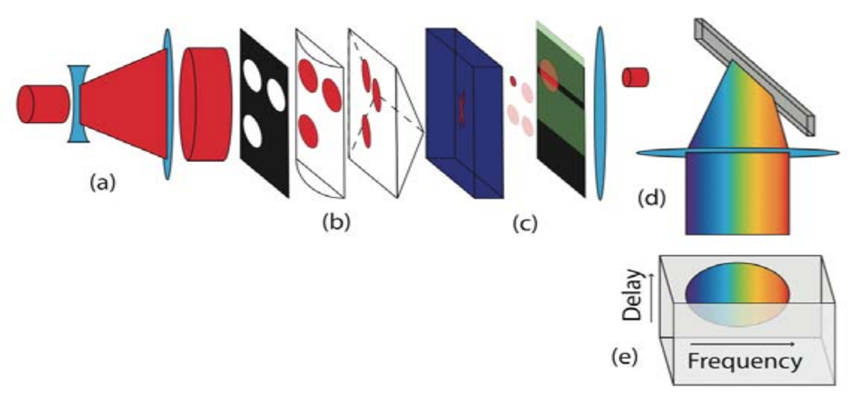
Following E. L. Saldin et al. PRST-AB 9, 050702 (2006)





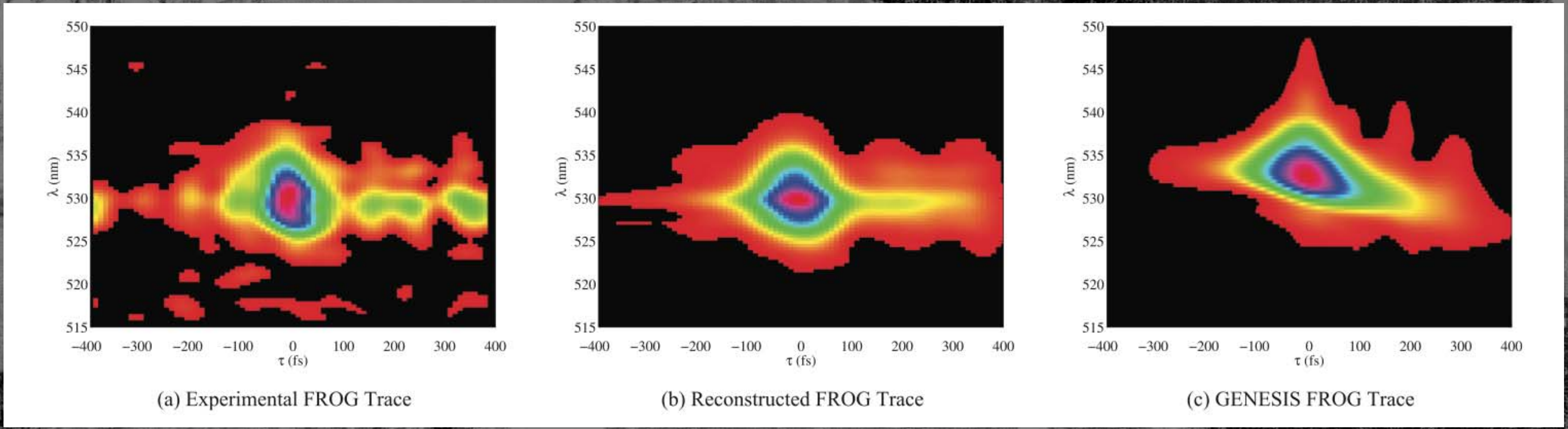
Measurement of pulse length

Assuming a Fourier limited pulse, the spectral width indicated a (rms) pulse length ≈ 50 fs, but a direct measurement of the pulse length was missing.



Collaboration with J. Rosenzweig, UCLA, G. Marcus designed and realized this FROG specifically for SPARC

G. Marcus et al., APL 101, 134102 (2012)



(a) Experimental FROG Trace

(b) Reconstructed FROG Trace

(c) GENESIS FROG Trace

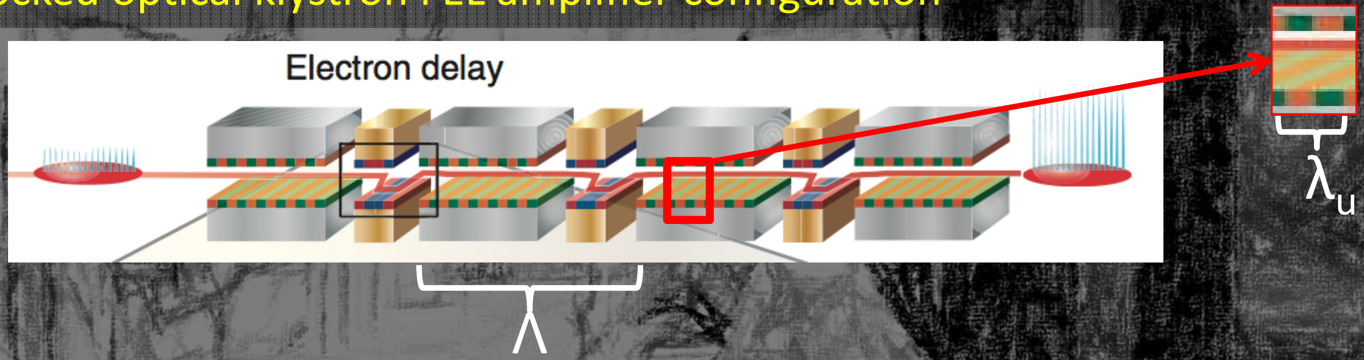
Measured (fwhm) pulse length of 98 fs (TBP ≈ 1.2).

Shorter than the cooperation length …

High harmonic attosecond pulse train amplification in a free electron laser

(B.W. J. McNeil et al. J. Phys. B 44 065404 (2011))

The attosecond structure of the HH seed can be amplified to saturation using a mode-locked optical klystron FEL amplifier configuration

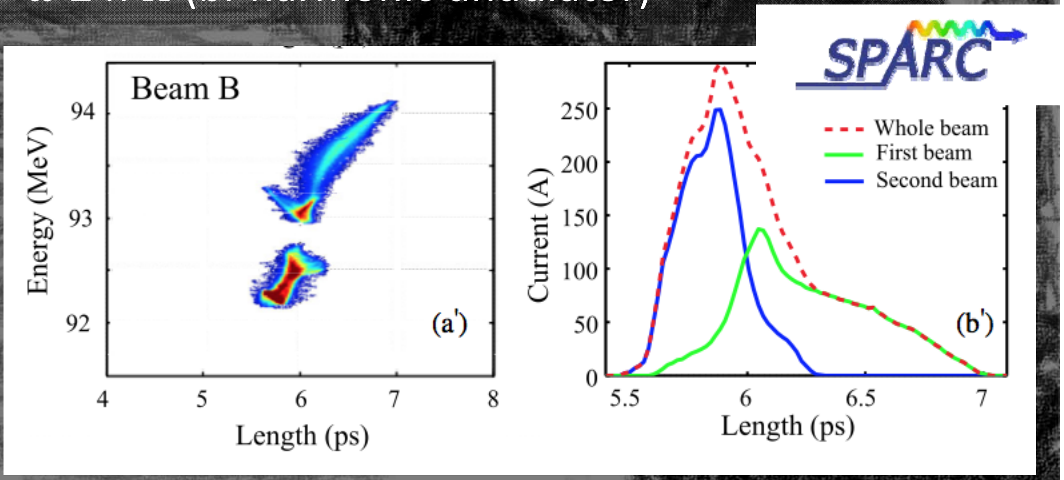


Two characteristic spatial periods lead to a frequency modulated emission spectrum, and gain function, with resonances at ω ± n Ω (bi-harmonic undulator)

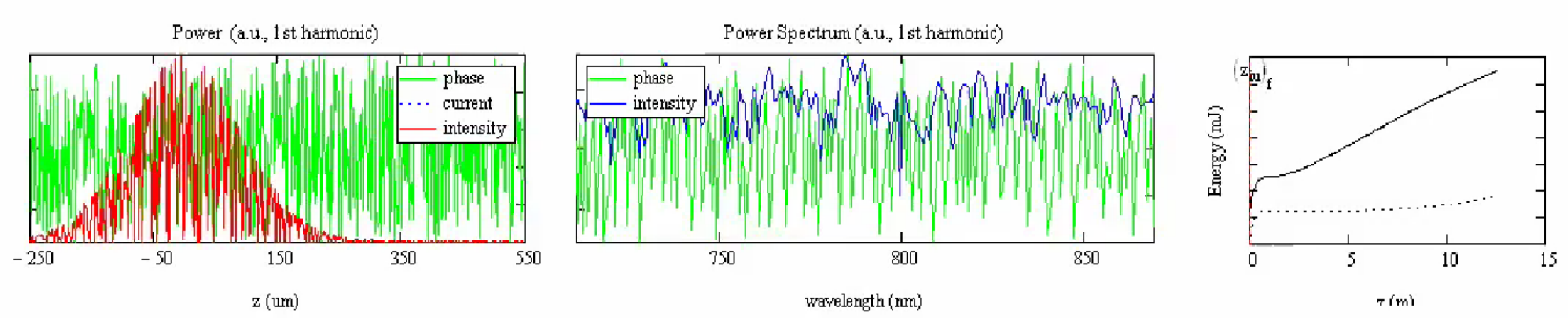
Similar situation is obtained lasing with two beams of different energies, at the same longitudinal position, if

$$\frac{\Delta\gamma}{\gamma} > 2\rho$$

V. Petrillo et al. PRL 111, 114802 (2013)

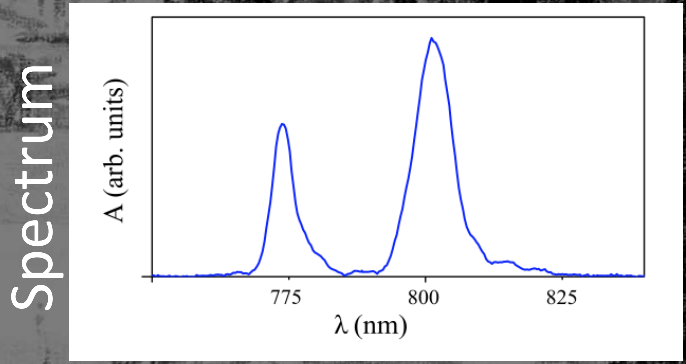


Perseo Simulation



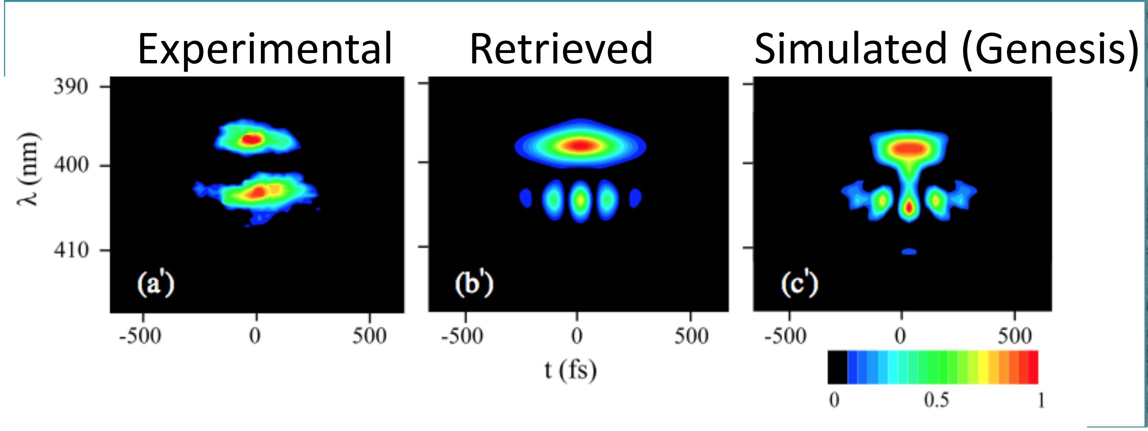
Experiment and analysis

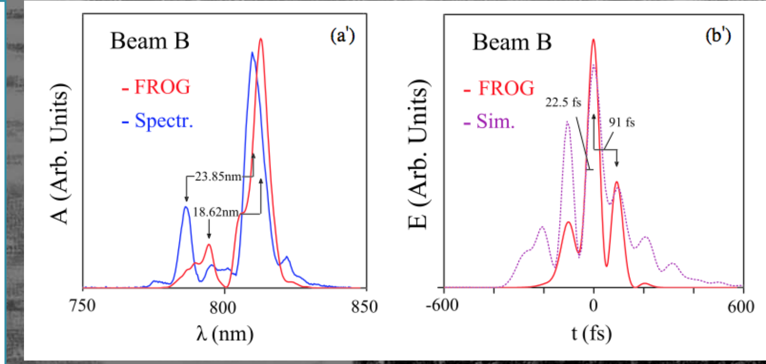
Energy (MeV)	93.04 ± 0.10
Total charge (pC)	165 ± 10
Emittance x (mm mrad)	1.68 ± 0.18
Emittance y (mm mrad)	1.81 ± 0.15
Energy spread (MeV)	0.59 ± 0.01
Energy spread single beamlet (MeV)	0.27 ± 0.01
Energy separation (MeV)	1.07 ± 0.14
Time duration (ps)	0.30 ± 0.01
Corrected FEL parameter single beamlet	1.5×10^{-3}
3D cooperation length single beamlet (μm)	12.5



R.M.S. spike width ≈ 22 fs,
3D coop length ≈ 42 fs

See F. Villa, MOP080



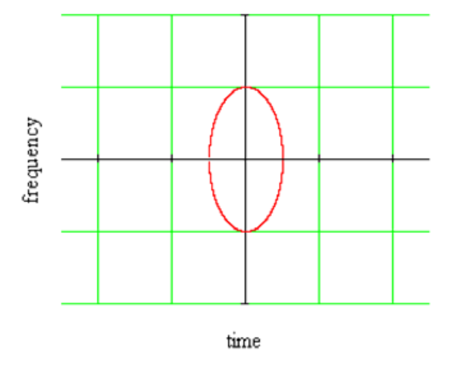


Combining gain bandwidth & seed:
Chirped Pulse Amplification

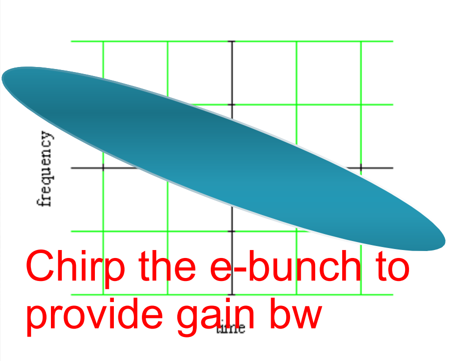
Ultrashort pulses can be obtained chirping the seed and the electron beam in phase space to widen the gain bandwidth and preserve resonance and optically re-compressing the pulse after amplification.

- The idea to use CPA for generating short and powerful FEL pulses from a seeded FEL has been proposed for the first time in *L. H. Yu at al, Phys. Rev. E 49 (1994)*
- We studied the application to a SASE FEL (SPARX) in *F. Frassetto, L. Giannessi, L. Poletto, Nucl. Inst. Meth. A 593 (2008)*.

Time-frequency diagram of the seed



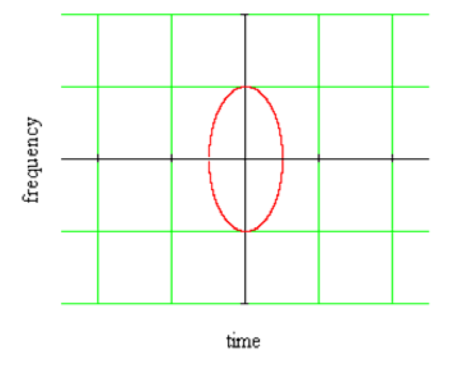
Stretch the seed with dispersion



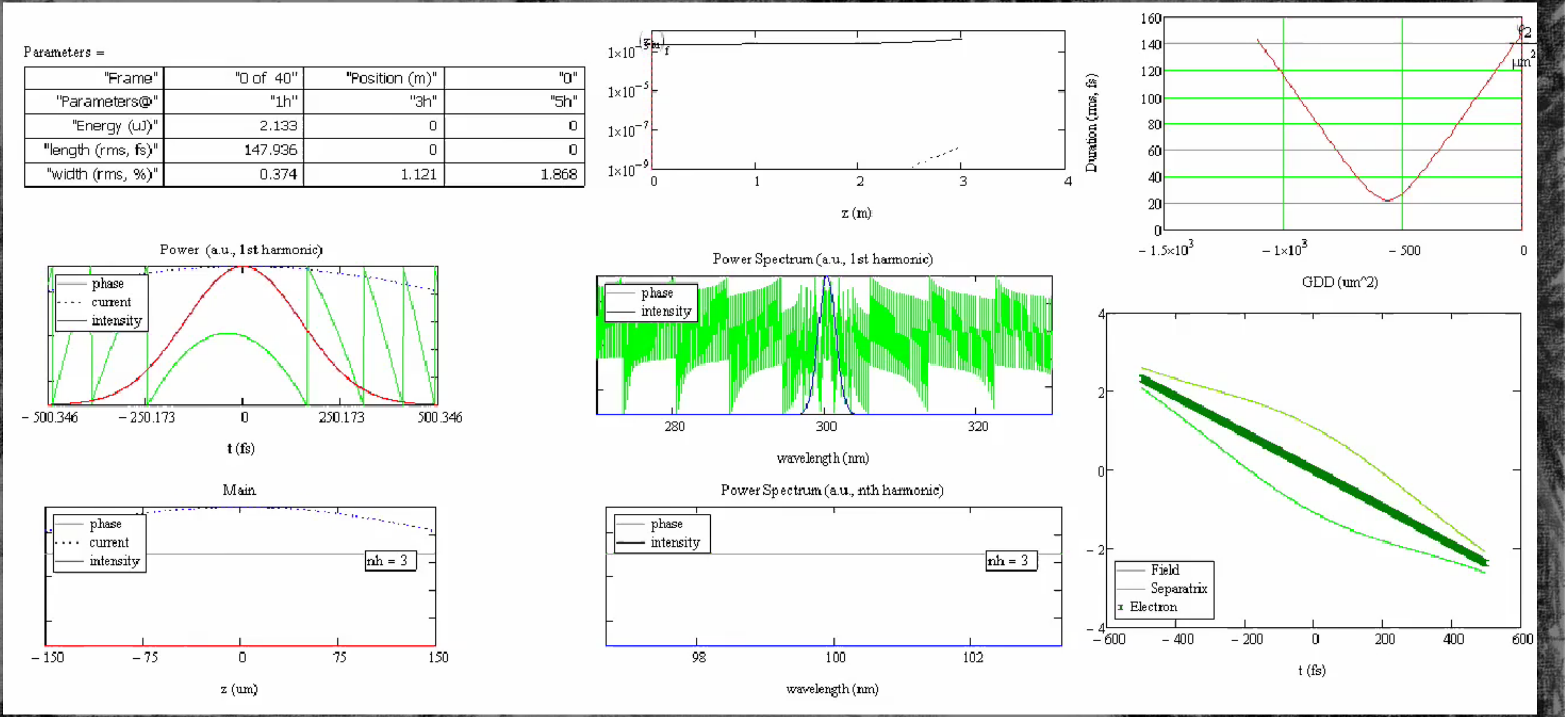
Chirp the e-bunch to provide gain bw

Amplification

Re- compression



Modulator

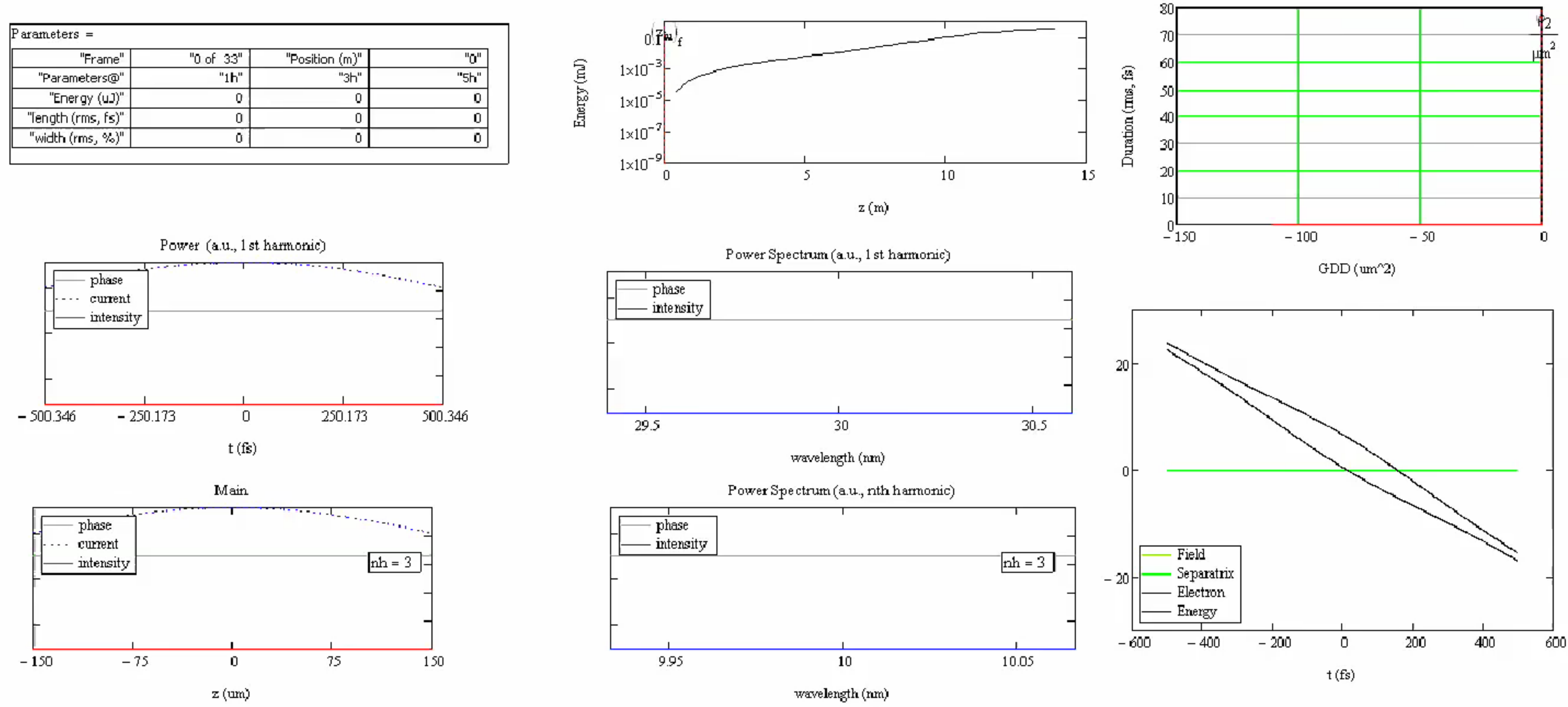


Parameters =

"Frame"	"0 of 40"	"Position (m)"	"0"
"Parameters@"	"1h"	"3h"	"5h"
"Energy (uJ)"	2.133	0	0
"length (rms, fs)"	147.936	0	0
"width (rms, %)"	0.374	1.121	1.868

FERMI FEL-1 configuration – D. Gauthier with Perseo

Radiator

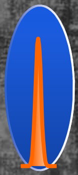


Parameters =

"Frame"	"0 of 33"	"Position (m)"	"0"
"Parameters@"	"1h"	"3h"	"5h"
"Energy (uJ)"	0	0	0
"length (rms, fs)"	0	0	0
"width (rms, %)"	0	0	0

CPA compared to short bunch

Higher Compression



PRO

- Low charge – low pulse energy
- High Current – higher gain, shorter gain length - Higher efficiency ($I^{1/3}$)
- Less sensitivity to beam parameters

CON

- Beam quality preservation with compr.
- Spectral quality preservation
- Stability & Time jitter

CPA

PRO

- Higher charge involved
- Higher e-beam quality because of lower compression
- Spectral quality

CON

- Beam quality preservation with large chirp & sensitivity to e-beam phase space lin.
- Efficiency of re-compression

FERMI FEL-1 and FEL-2

- Project idea on CPA (Coord. G. De Ninno) - collaborations with UN. Padova, Un. N. Gorica, LOA, I*nstituto Plasmas e Fusão Nuclear, Lisbona* & Max Planck for a test experiment @ 26 nm - **See G. De Ninno MOP073**
- Future steps following proposal from A. Cavalleri & A. Cavalieri (MPI) for dedicated beamline for ultrashort pulses & CPA on FEL-2 (up to 500 eV) (and FEL-1 at 90-100 eV)

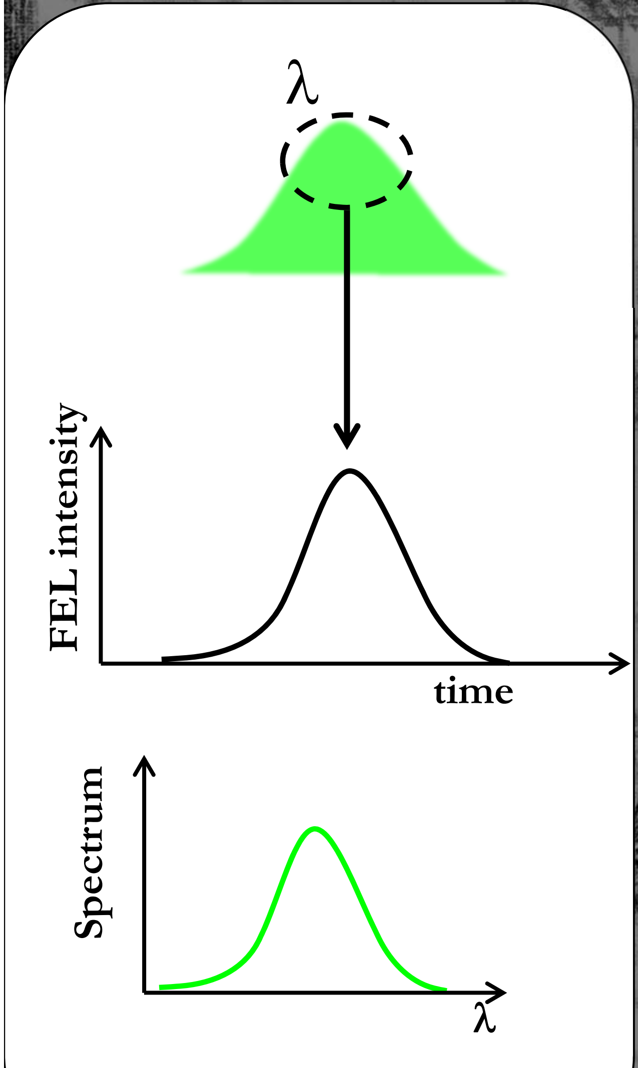
Pulse splitting and superradiance

SATURATION

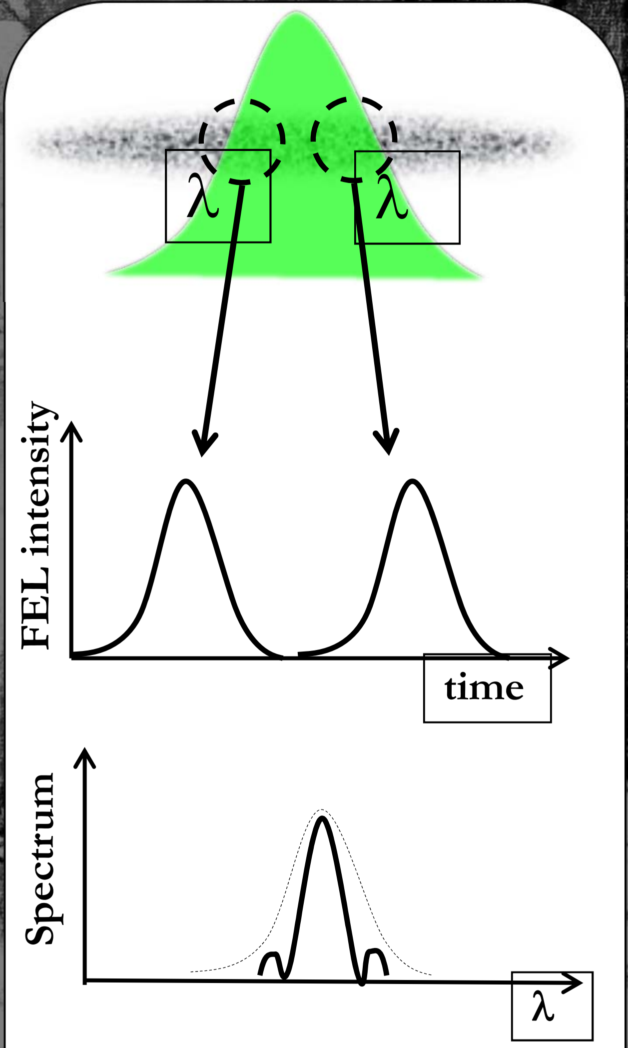
FEL pulse splitting by long. synchrotron oscillation

M. Labat et al., PRL 103, 264801 (2009)

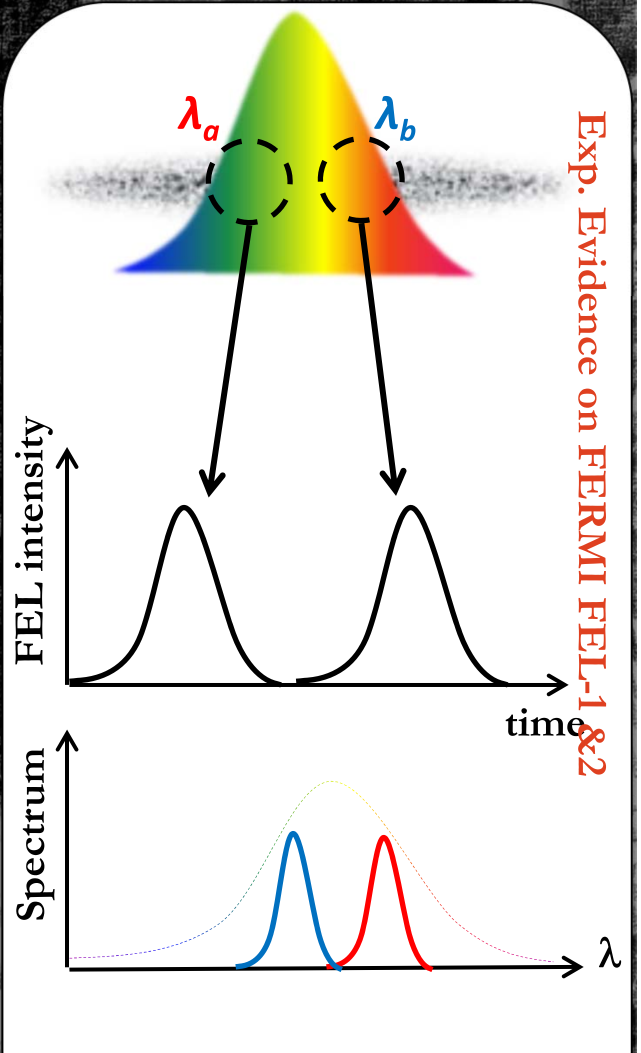
G. De Ninno et al. PRL 110, 064801, 2013



Standard HGHG



Increasing seed power



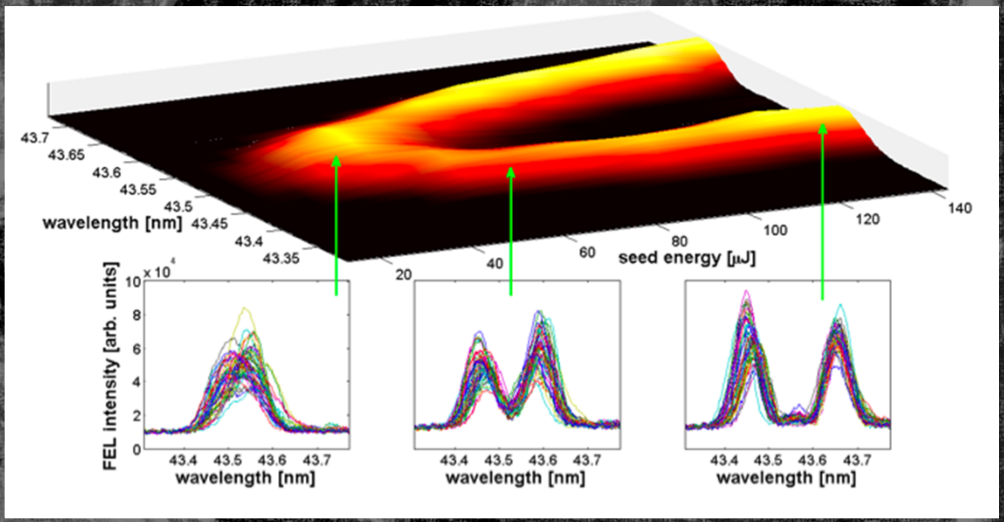
Exp. Evidence on FERMI FEL-1&2

Chirped seed

Pulse splitting observed at FERMI since winter 2010…

Seed frequency chirp generated by propagating through the different optical components (lenses, windows), and by self-phase modulation due to high intensity

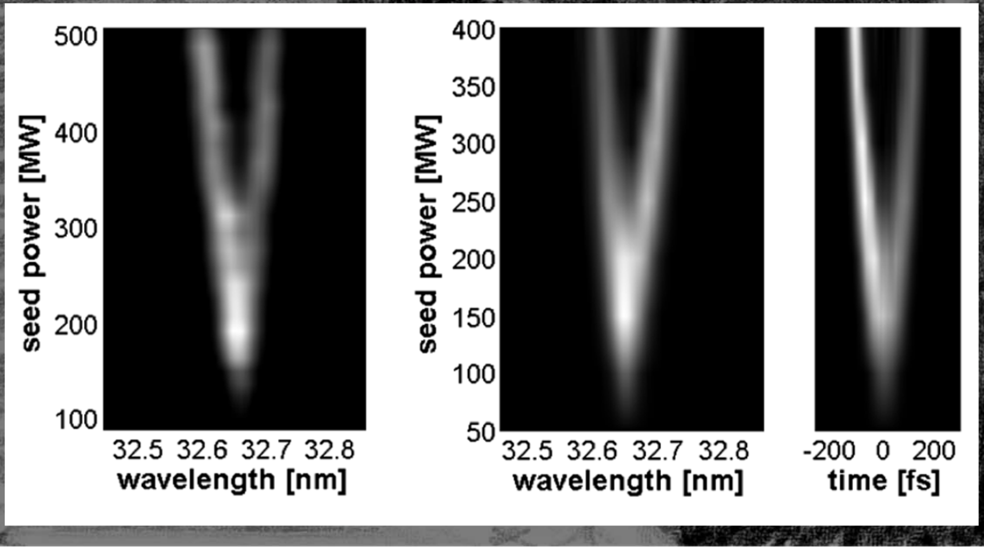
B. Mahieu et al. Optics Express 21, 22728 (2013)



Temporal separation limited by seed pulse length:

- Generating long (chirped) seed pulses with significant local power tails is an issue.
- High intensity may give multiple local maxima (observed)

Experiment PERSEO simulations

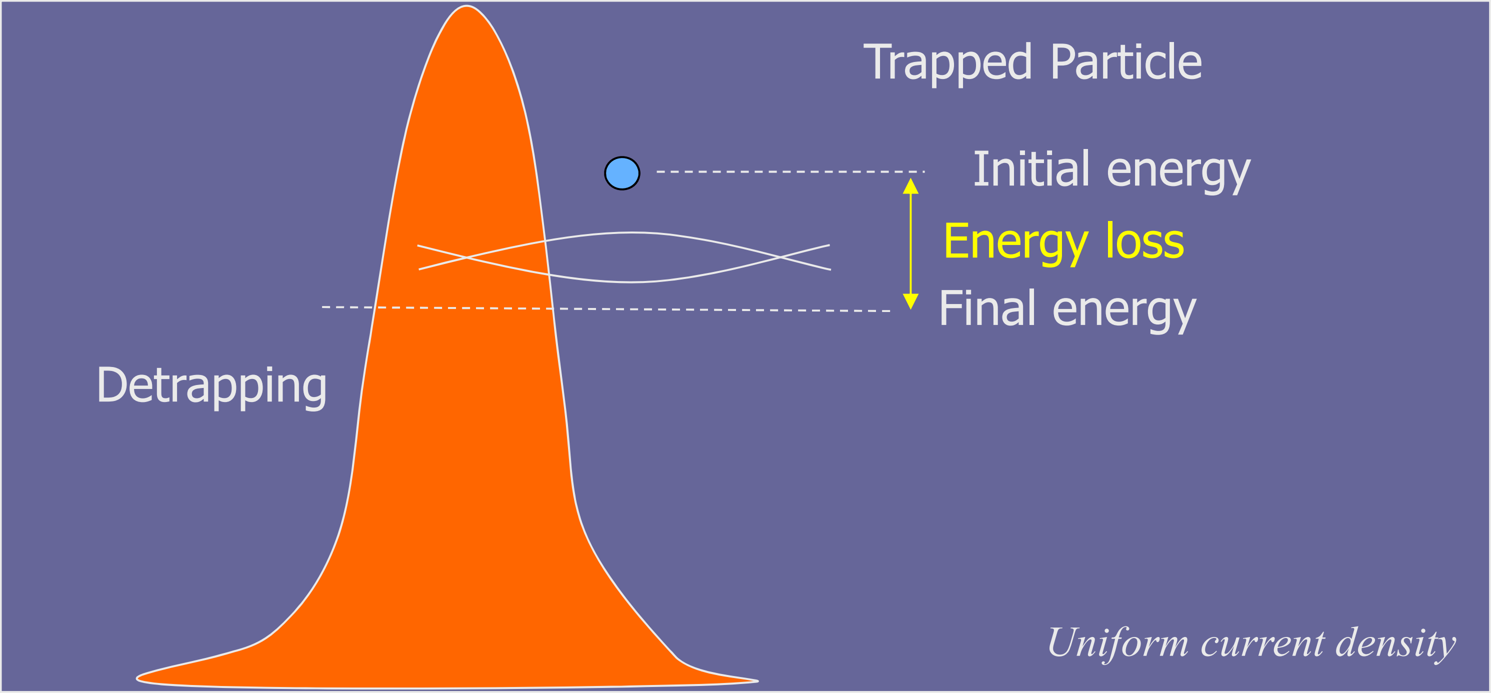


Superradiance

Pioneered by R. Bonifacio and co-workers see e.g. *R. Bonifacio et al. Riv. N. Cim.* ***13****, 1 (1990)*

- **Slippage:** **The light advances over the electrons of a distance Nλ in N undulator periods**
- **Saturation:** **When the FEL laser power reaches ~ρP_{E}, saturation occurs: there is a cyclic energy exchange between electrons and field (in steady state regime)**

If the pulse length is comparable to the distance covered in a synchrotron period



The pulse energy grows with slippage distance & depth of potential bucket

Pulse shape not determined by the seed: after saturation the seed turns into a solitary wave (in scaled coordinates)

Scaling relations (in 1-D)

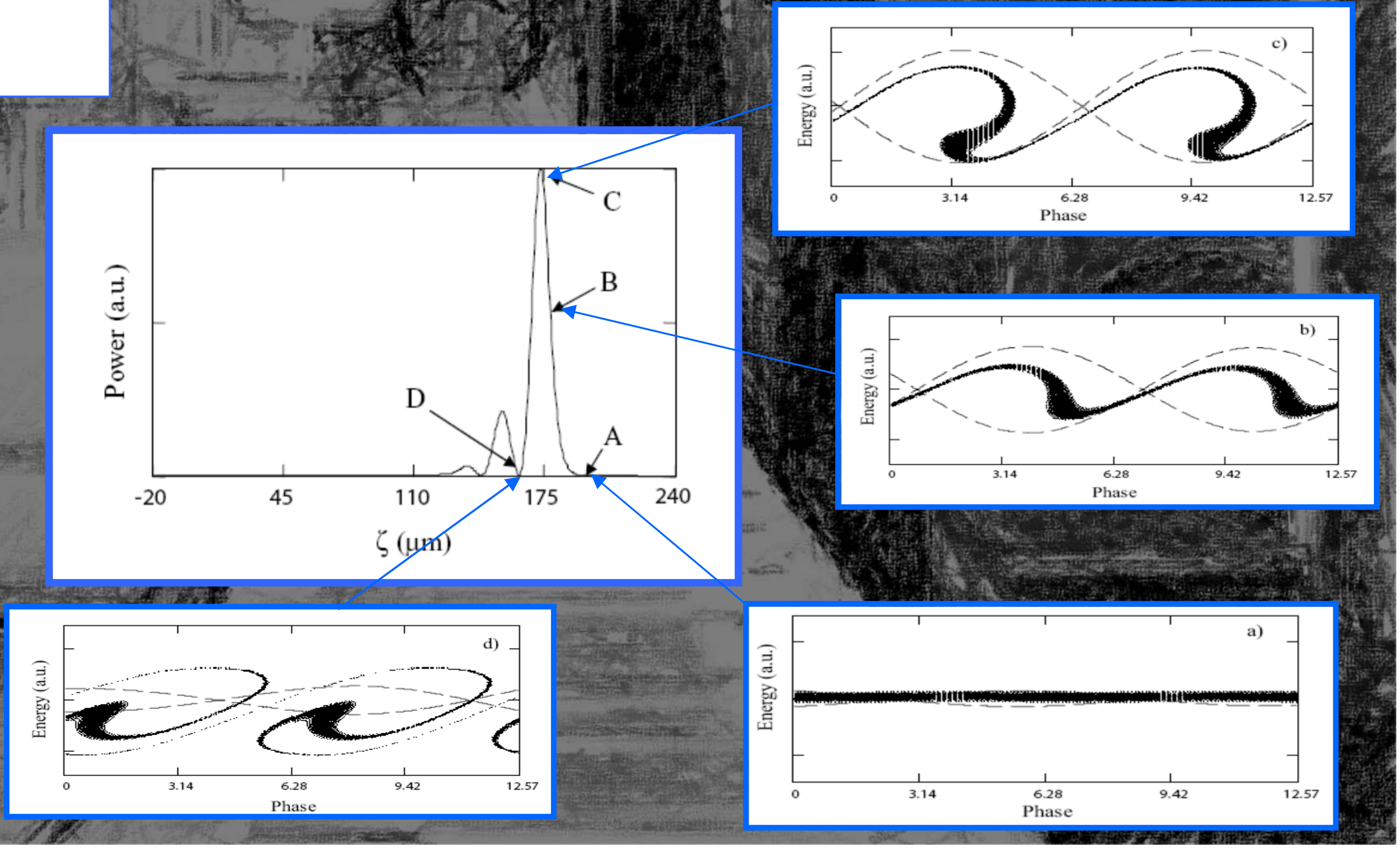
$Duration \quad \sigma_t \propto z^{-1/2}$

$Energy \quad E \propto z^{3/2}$

$Power \quad P \propto z^2$

L. Giannessi, P. Musumeci, S. Spampinati, JAP 98, 043110 (2005)

1. Emission of high order harmonics
2. Behavior in a FEL cascaded configuration



See Xi Yang, Poster MOP079

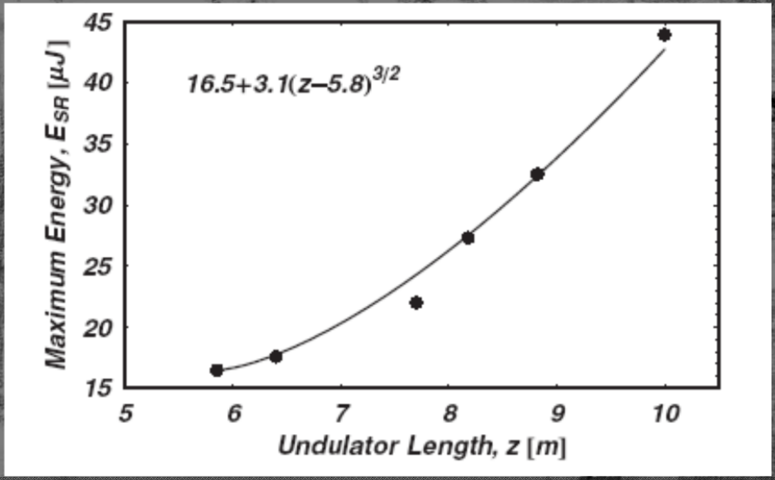
Experimental results:

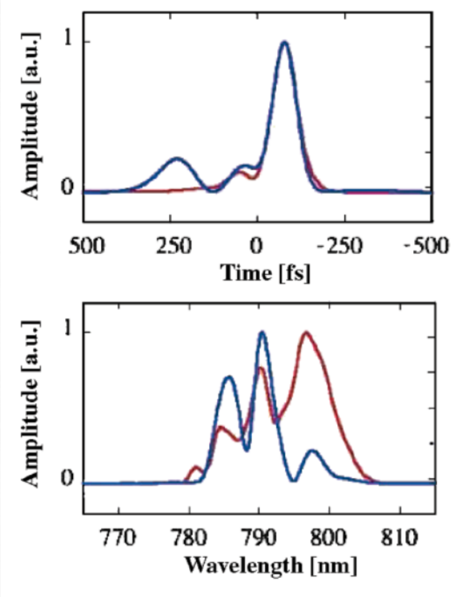
Longitudinal focusing

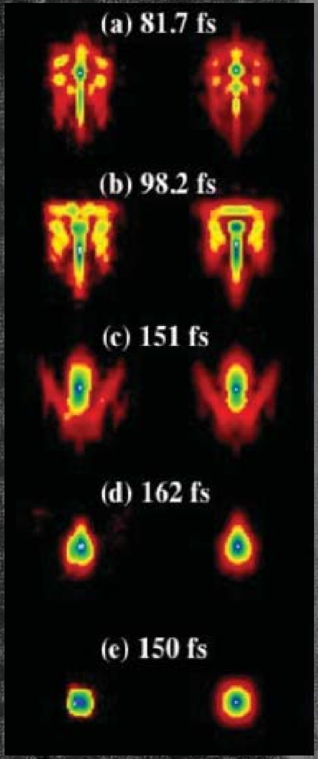
BNL - SDL: *T. Watanabe et al. PRL 98, 034802 (2007)*

Pulse shape and spectrum

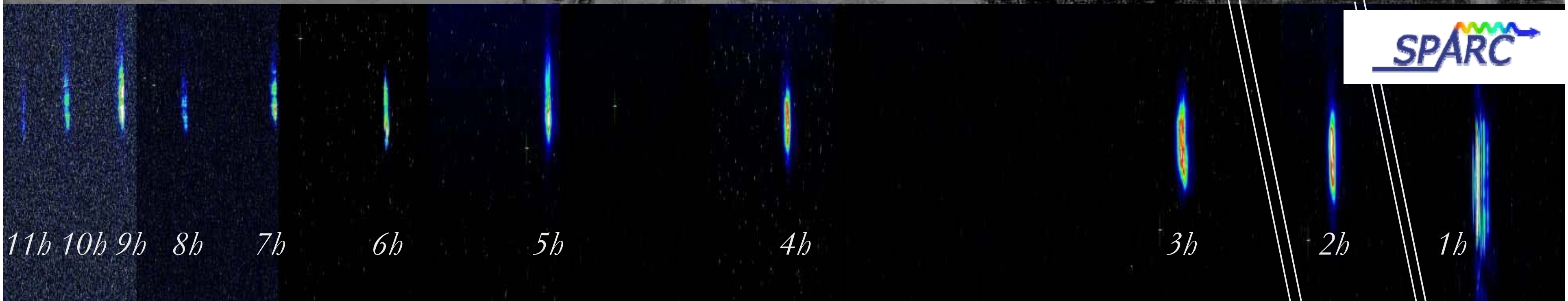
Pulse energy scaling







Frascati - SPARC: *L. Giannessi et al. PRL 108, 164801 (2012)*



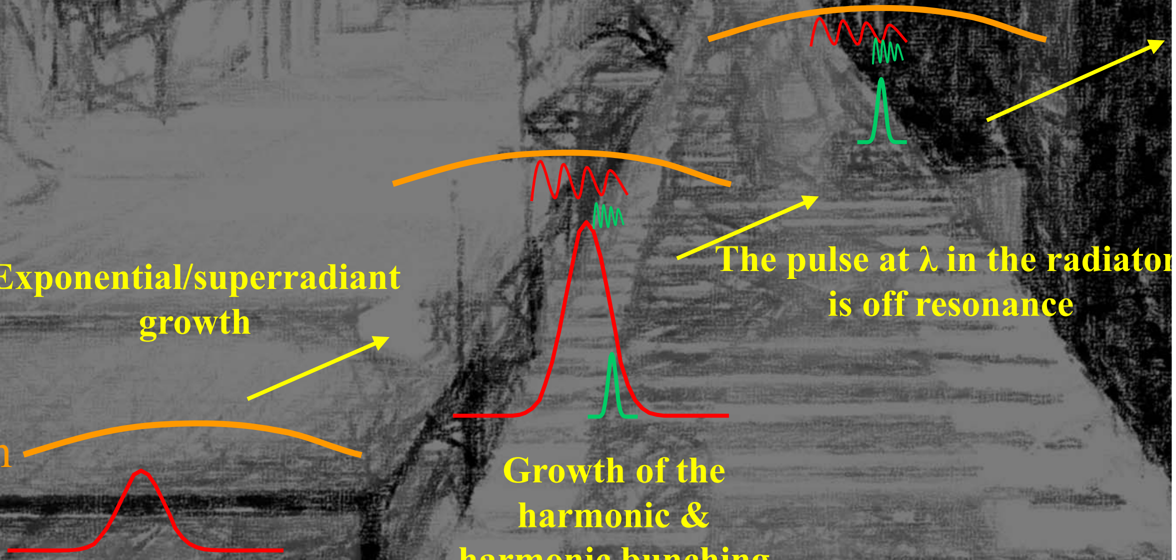
High order harmonics 400 nm ➔ 36 nm

Evolution of a superradiant pulse in a cascade

Seed

Modulator

Radiator



“Fresh Bunch I

The pulse slips

fresh part

Short pulse at λ/n by CHG: E~z^2

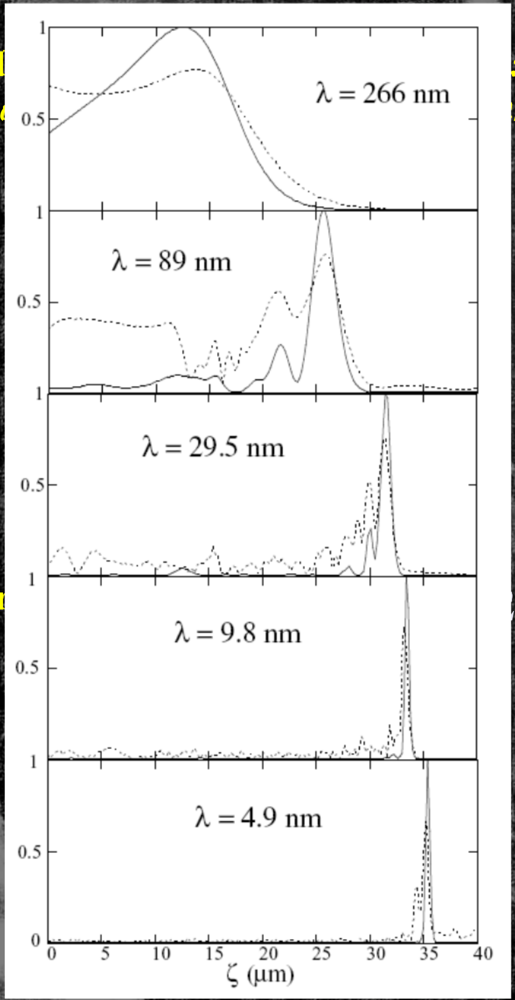
The pulse at λ in the radiator is off resonance

Exponential/superradiant growth

e⁻ beam

Growth of the harmonic & harmonic bunching

Seed



L. Giannessi, P. Musumeci, S. Spampinati, JAP 98, 043110 (2005)

Harmonic Cascaded FEL

L. Giannessi, P. Musumeci New Journal of Physics ***8*** *(2006) 294*

Resonant at λ_1

UM1 → **UM2**

Bunching at $\lambda_n = \dfrac{\lambda_1}{n}$

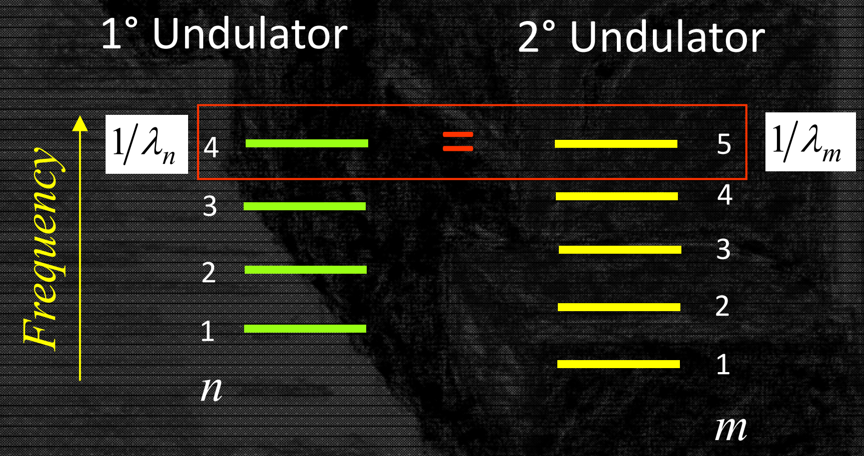
Resonant at $\lambda_2 = \dfrac{m}{n}\lambda_1, \quad m \neq n$

Emitted wavelength: $\lambda_m = \dfrac{\lambda_2}{m} = \lambda_n$

Advantages:

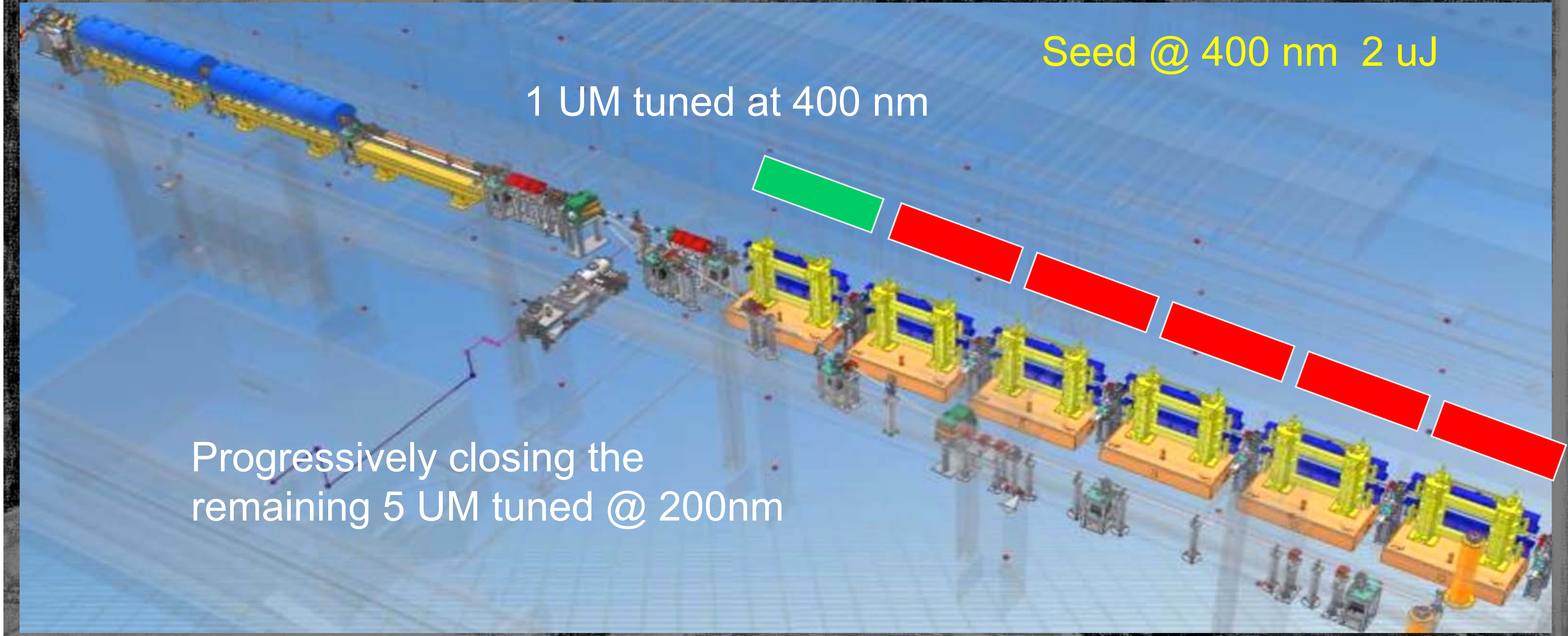
1. Higher order harmonic coupling in the final radiator extends the wavelength operation range
2. Larger slippage in the final radiator. Pulse energy is proportional to slippage.

Harmonics Spectrum of the two undulators



Superradiant Cascade at SPARC

L. Giannessi et al. PRL 110, 044801 (2013)



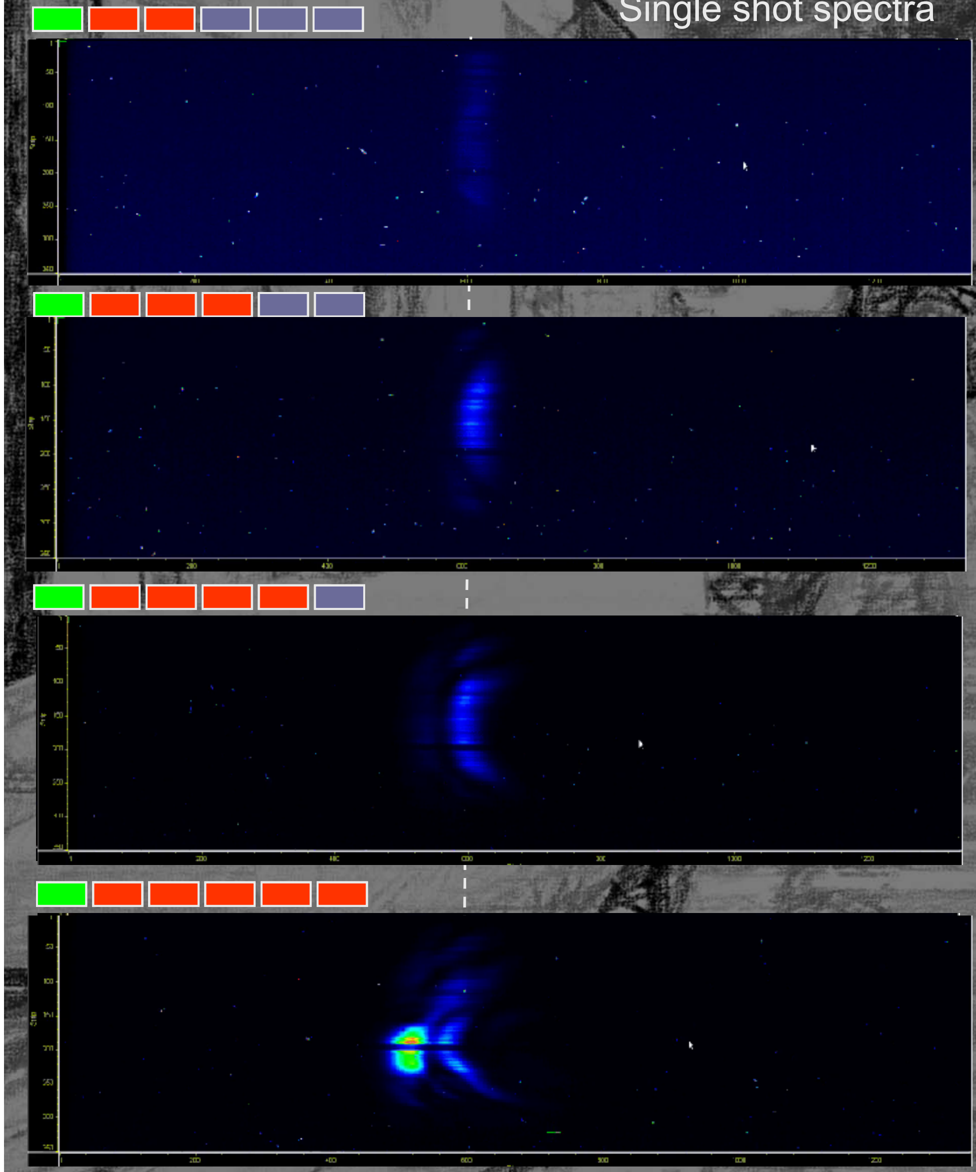
Seed @ 400 nm 2 uJ

1 UM tuned at 400 nm

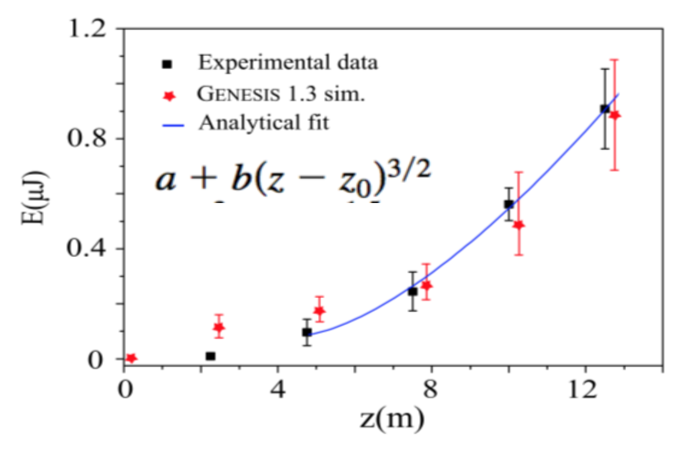
Progressively closing the
remaining 5 UM tuned @ 200nm

Superradiant Cascade

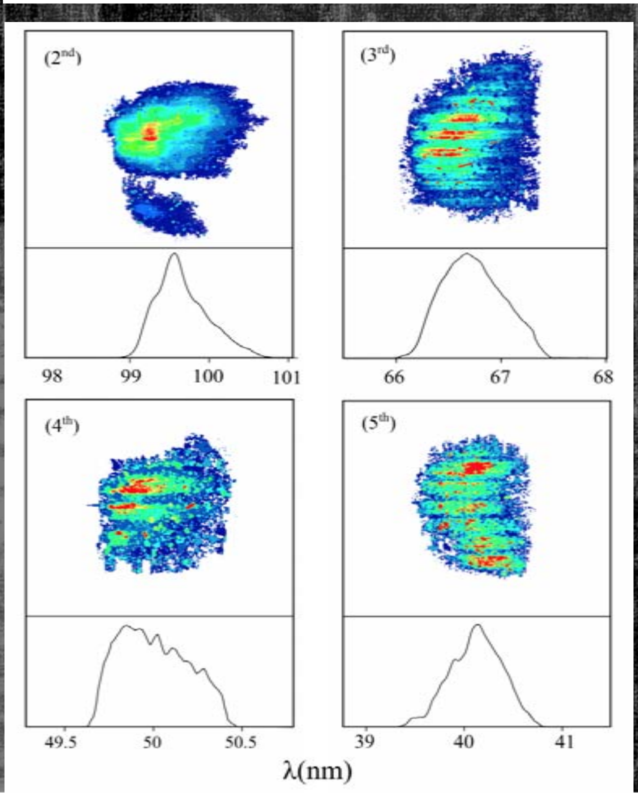
Single shot spectra



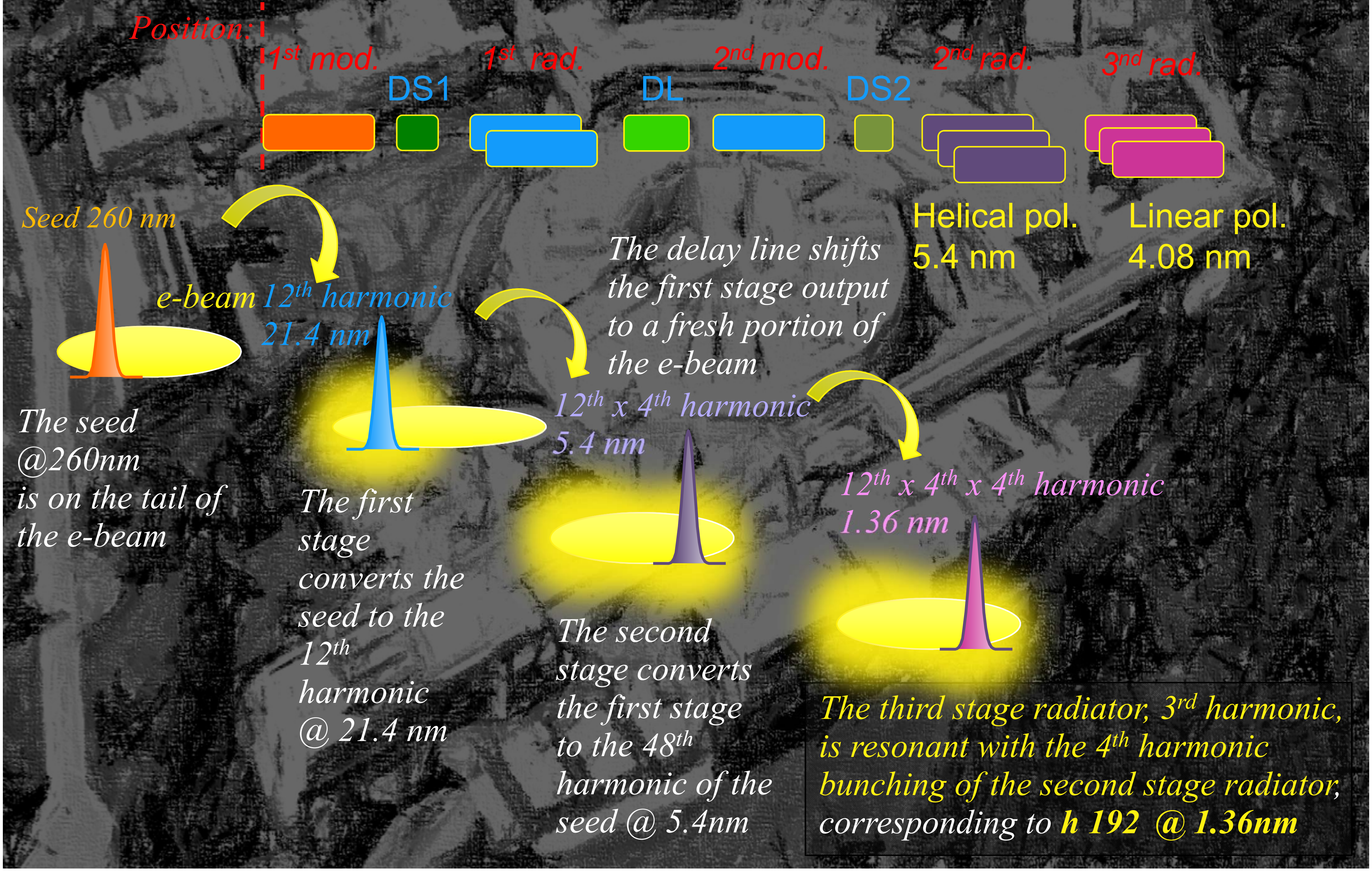
Energy scaling α $z^{3/2}$



High order harmonics



FERMI FEL-2: Fresh bunch injection & harmonic cascade



Position:

1st mod.

DS1

1st rad.

DL

2nd mod.

DS2

2nd rad.

3rd rad.

Helical pol.
5.4 nm

Linear pol.
4.08 nm

Seed 260 nm

e-beam

12th harmonic
21.4 nm

The delay line shifts the first stage output to a fresh portion of the e-beam

12th x 4th harmonic
5.4 nm

12th x 4th x 4th harmonic
1.36 nm

The seed @260nm is on the tail of the e-beam

The first stage converts the seed to the 12th harmonic @ 21.4 nm

The second stage converts the first stage to the 48th harmonic of the seed @ 5.4nm

The third stage radiator, 3rd harmonic, is resonant with the 4th harmonic bunching of the second stage radiator, corresponding to ***h 192 @ 1.36nm***

FEL-2 - June 2014 – RUN 20

Not Ideal:

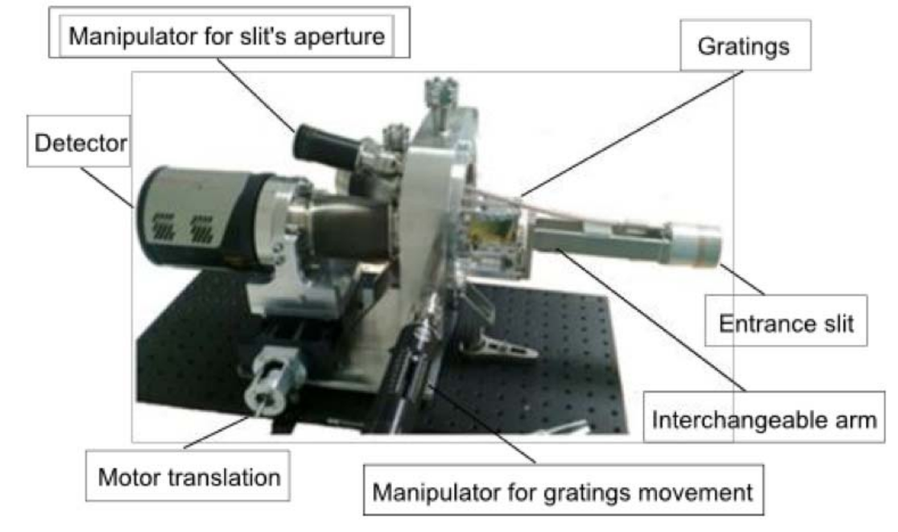
- The relatively long seed pulse (120-140 fs) do not ensure a “single spike” superradiant pulse
- Sudden cascade transitions by factors of x10 or more do not leave sufficient propagation length for shortening the pulse from one stage another

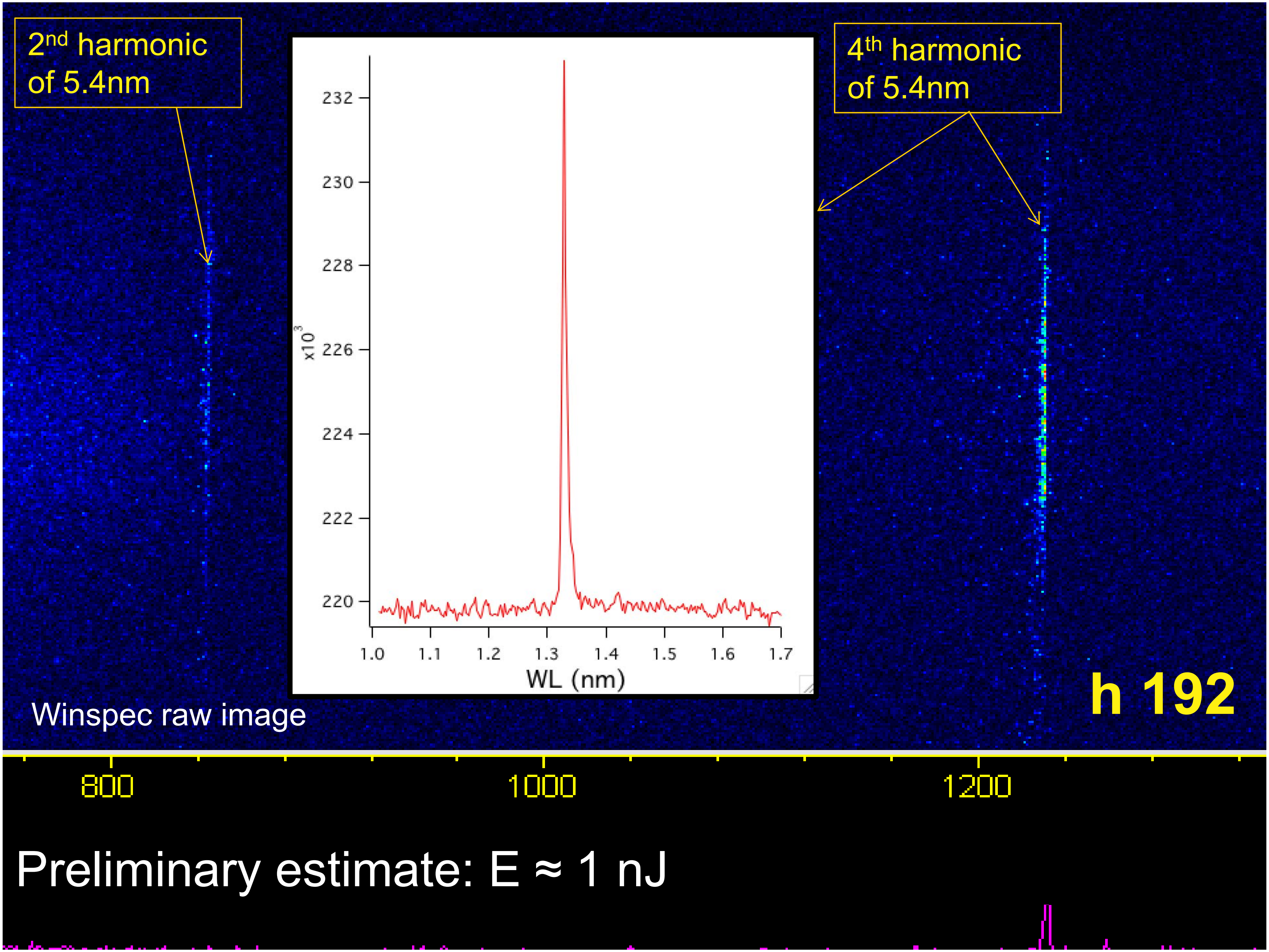
LDM Beamline

(C. Callegari resp., with support from M. Coreno, P. Finetti, F. Frassetto, R. Godnig, P. Miotti, L. Poletto)

Dedicated Spectrometer
High sensitivity CCD detector
Spectral range up to ≈ 1 keV

See P. Finetti, MOP020





Preliminary estimate: E ≈ 1 nJ

Contributors …

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