DE LA RECHERCHE À L'INDUSTRIE

CHIRPED PULSE AMPLIFICATION FOR SHORT VUV FEL PULSES AT FERMI@ELETTRA

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and
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(On behalf of the FERMI CPA Collaboration)

LASERLAB IV Joint research Action

Obj. 3: Advanced coherent XUV and X-Ray sources

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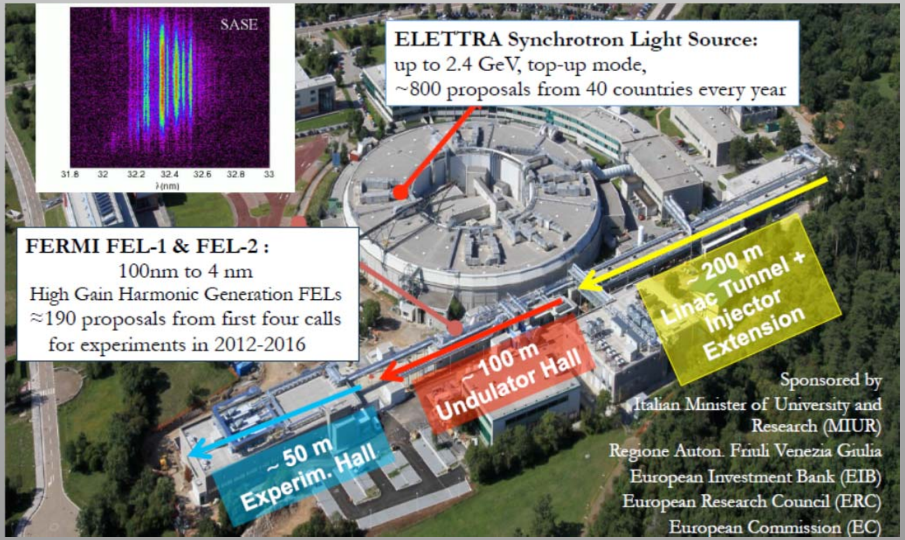
Talk Outline

- Motivation and theoretical background
- Aim of the first CPA experiment at FERMI :
  Scientific, Technical and Operational challenge
    - Electron-beam, seed and FEL preparation
    - The compressor
    - Temporal duration measurement Set-up
- **Results of the first CPA experiment at FERMI and next step**
- Conclusions
- The FERMI CPA collaboration

Motivations

- Generate sub-femtosecond high peak power XUV pulses
- Fully control the spectro-temporal features of generated radiation
- Extend towards very high photon energies (water window)



ELETTRA Synchrotron Light Source:
up to 2.4 GeV, top-up mode,
~800 proposals from 40 countries every year

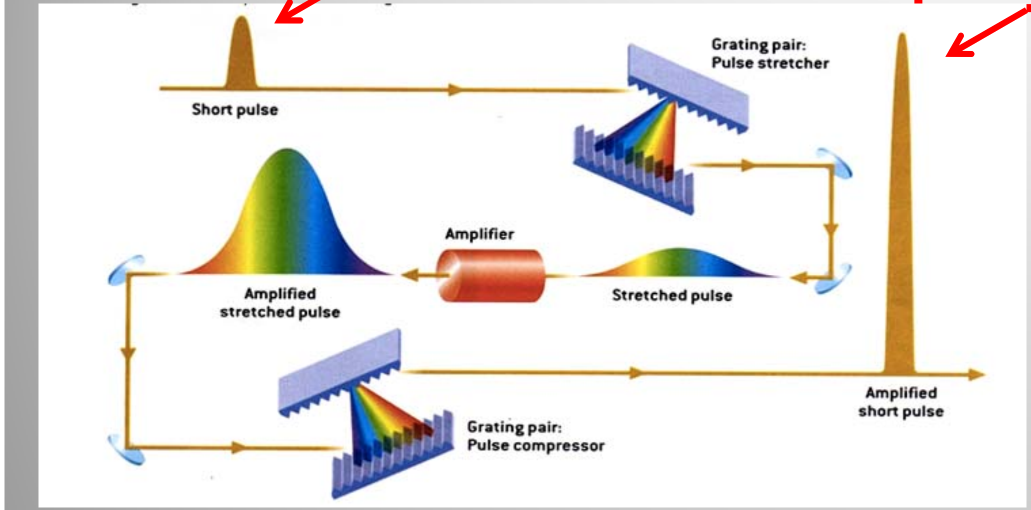
FERMI FEL-1 & FEL-2 :
100nm to 4 nm
High Gain Harmonic Generation FELs
≈190 proposals from first four calls
for experiments in 2012-2016

Sponsored by
Italian Minister of University and Research (MIUR)
Regione Auton. Friuli Venezia Giulia
European Investment Bank (EIB)
European Research Council (ERC)
European Commission (EC)

Chirped Pulse Amplification in solid-state lasers and in FELs

CPA in a solid-state laser….

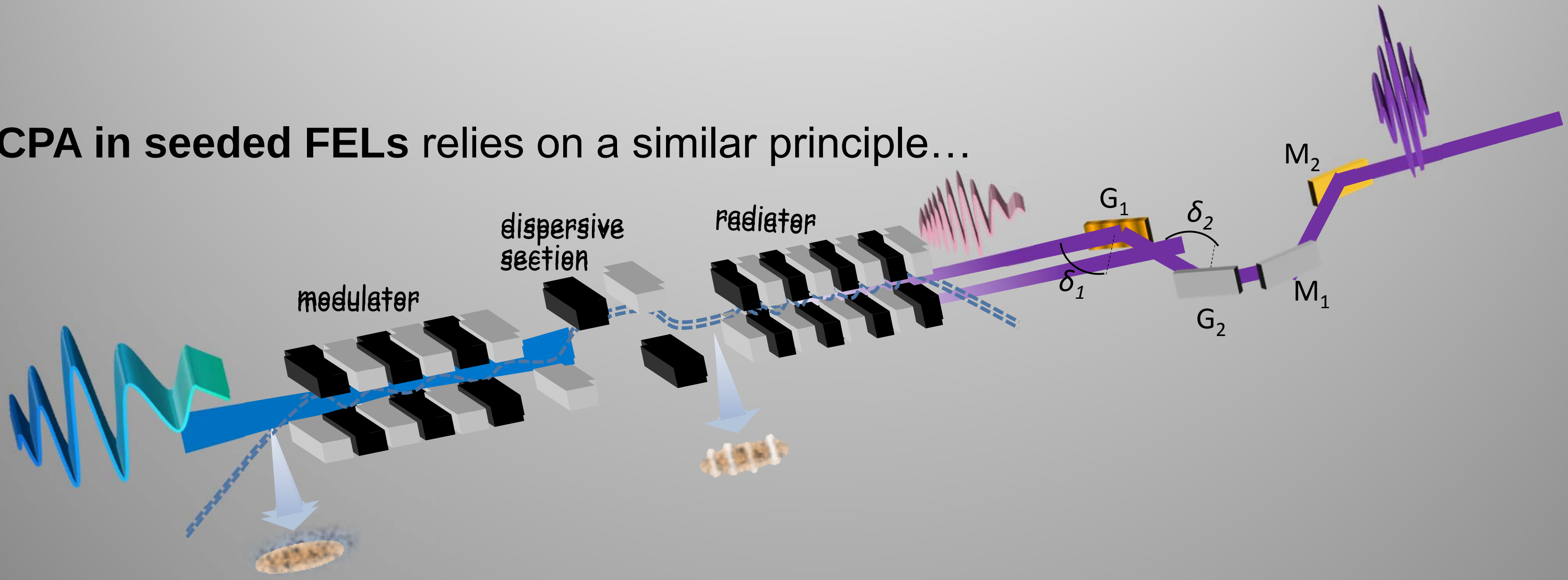
Similar Bandwidth and input/output duration



Chirped Pulse Amplification in solid-state lasers and in FELs

Yu, L.H. et al, Phys Rev. E, 49 (5), 4480 (1994)
G. Stupakov, SLAC-PUB-14639 (2011)
Ratner, D. et al.. Phys. Rev. STAB 15, 030702 (2012).

CPA in seeded FELs relies on a similar principle…



For a generic chirped pulse…

In general, the electric field of a chirped pulse reads

group delay dispersion (GDD)

$$\hat{E}(\omega)\sim\exp\left(-\frac{\omega^2}{2\sigma_\omega^2}\right)\exp\left(-\frac{1}{4}i\beta\omega^2\right),$$

spectral width

In the time domain

chirp coefficient

$$E(t)\sim\exp\left(-\frac{t^2}{2\sigma_t^2}\right)\exp\left(-i\Gamma t^2\right),$$

temporal width

$$\begin{cases}\Gamma=\dfrac{\beta}{4/\sigma_\omega^4+\beta^2}\\ \sigma_t^2=\dfrac{1}{\sigma_\omega^2}+\dfrac{1}{4}\beta^2\sigma_\omega^2\end{cases}\xrightarrow{\beta<<2/\sigma_\omega^2}\begin{cases}\Gamma\approx 0\\ \sigma_t\approx\dfrac{1}{\sigma_\omega}\end{cases}$$

small-chirp regime

(transform limit)

For a generic chirped pulse…

In general, the electric field of a chirped pulse reads

group delay dispersion (GDD)

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In the time domain

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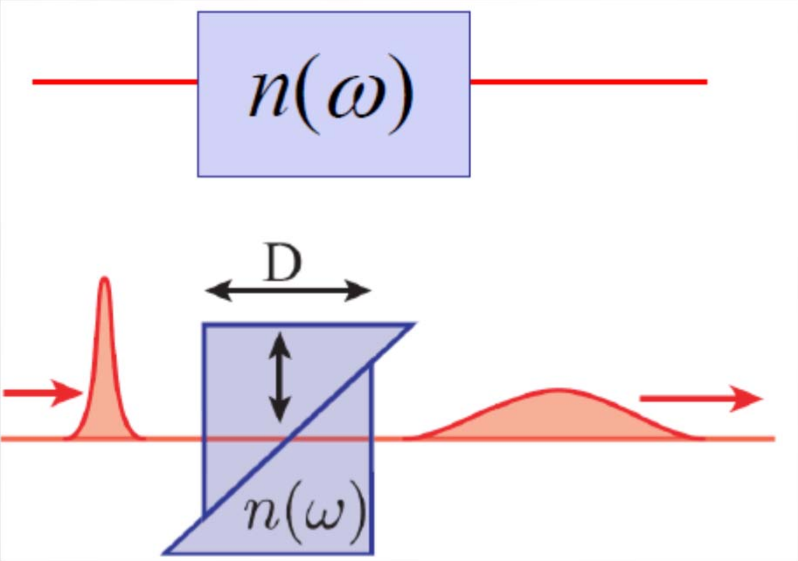
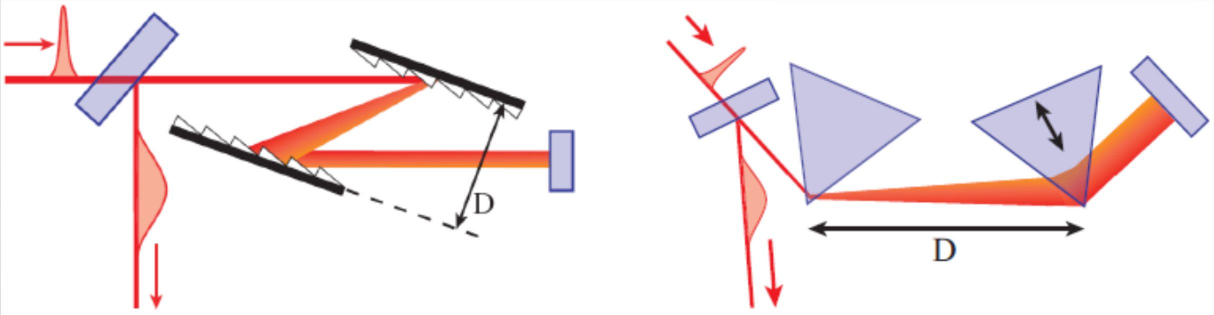
$$\begin{cases}\Gamma=\dfrac{\beta}{4/\sigma_\omega^4+\beta^2}\\[2ex] \sigma_t^2=\dfrac{1}{\sigma_\omega^2}+\dfrac{1}{4}\beta^2\sigma_\omega^2\end{cases}\xrightarrow[\text{strong-chirp regime}]{\beta>>2/\sigma_\omega^2}\begin{cases}\Gamma\approx\dfrac{1}{\beta}\\[2ex] \sigma_t\approx\dfrac{1}{2}\beta\ \sigma_\omega\end{cases}$$

Controlling the Laser Chirp

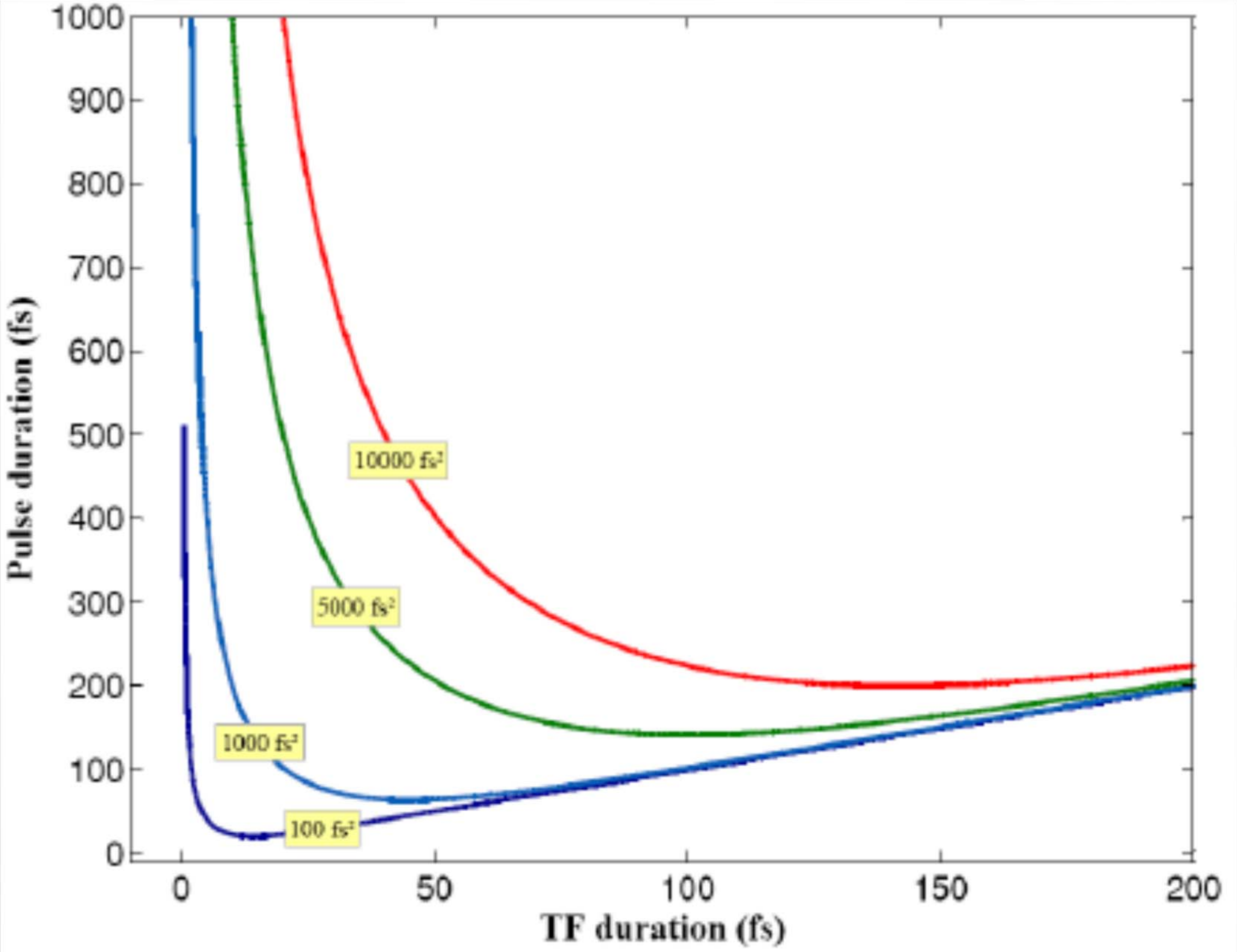


High Dispersive Materials



Prisms or Diffraction Gratings pairs

Controlling the Laser Chirp



For a seeded FEL…

Strong-chirp regime

$$\begin{cases} \sigma_t \approx \frac{1}{2}\beta\ \sigma_\omega \\ \Gamma \approx \frac{1}{\beta} \end{cases}$$

Strongly-chirped seed → Strongly-chirped FEL

Moreover :

$$(\sigma_t)_{FEL}^{noCPA} = \frac{(\sigma_t)_{seed}}{n^\alpha}$$

$$n = \frac{\lambda_{FEL}}{\lambda_{seed}} \approx 10$$ *harmonic number*

$$\alpha \approx 1/3$$

(for "moderate" FEL saturation: Stupakov's law)

$$\Gamma_{FEL} = n\Gamma_{seed} \longrightarrow \beta_{FEL} \approx \beta_{seed} / n$$

Combining previous relations…

Bandwidth increase/pulse shortening in CPA FEL

$$\boxed{(\sigma_\omega)_{FEL} = n^{1-\alpha}(\sigma_\omega)_{seed}}$$

FEL bandwidth larger than seed bandwidth!

*seed pulse duration (**no chirp**)*

$$\boxed{(\sigma_t)_{FEL}^{CPA} = \frac{(\sigma_t)_{seed}^{nochirp}}{n^{1-\alpha}}}$$

*FEL pulse duration **after compression***

Bandwidth increase/pulse shortening in CPA FEL

CPA

$$\left(\sigma_t\right)_{FEL}^{CPA} = \frac{\left(\sigma_t\right)_{seed}^{nochirp}}{n^{1-\alpha}}$$

no CPA

$$\left(\sigma_t\right)_{FEL}^{noCPA} = \frac{\left(\sigma_t\right)_{seed}}{n^{\alpha}}$$

Typically $\alpha \approx 1/3$

$$\left(\sigma_t\right)_{FEL}^{CPA} \approx \frac{1}{n^{2/3}}$$

$$\left(\sigma_t\right)_{FEL}^{noCPA} \approx \frac{1}{n^{1/3}}$$

Goal of the first CPA experiment at FERMI

Demonstrate the feasibility of the CPA scheme in a seeded FEL

Check the validity of the scaling law

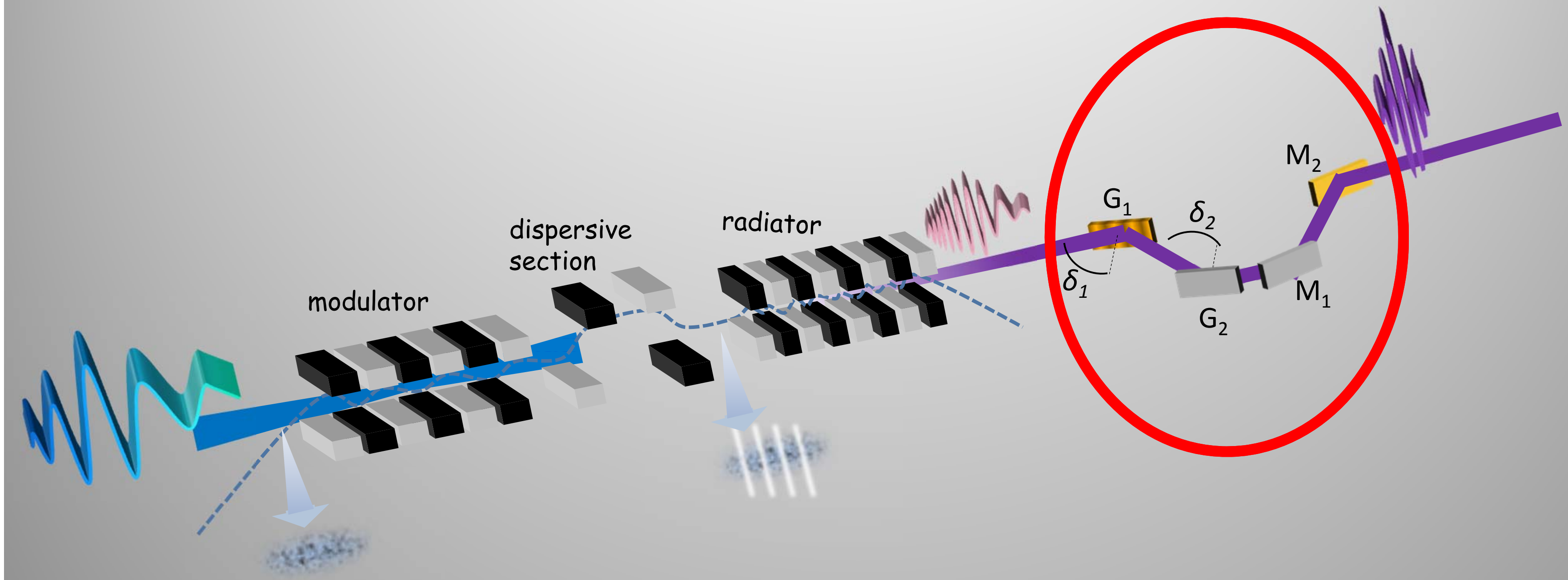
$$(\sigma_t)^{CPA}_{FEL} = \frac{(\sigma_t)^{nochirp}_{seed}}{n^{1-\alpha}}$$

Optimize every single stage of the experimental Setup

- o Electron and Laser seed pulse
- o The Compressor
- o Pulse Duration Measurement Tecnniques

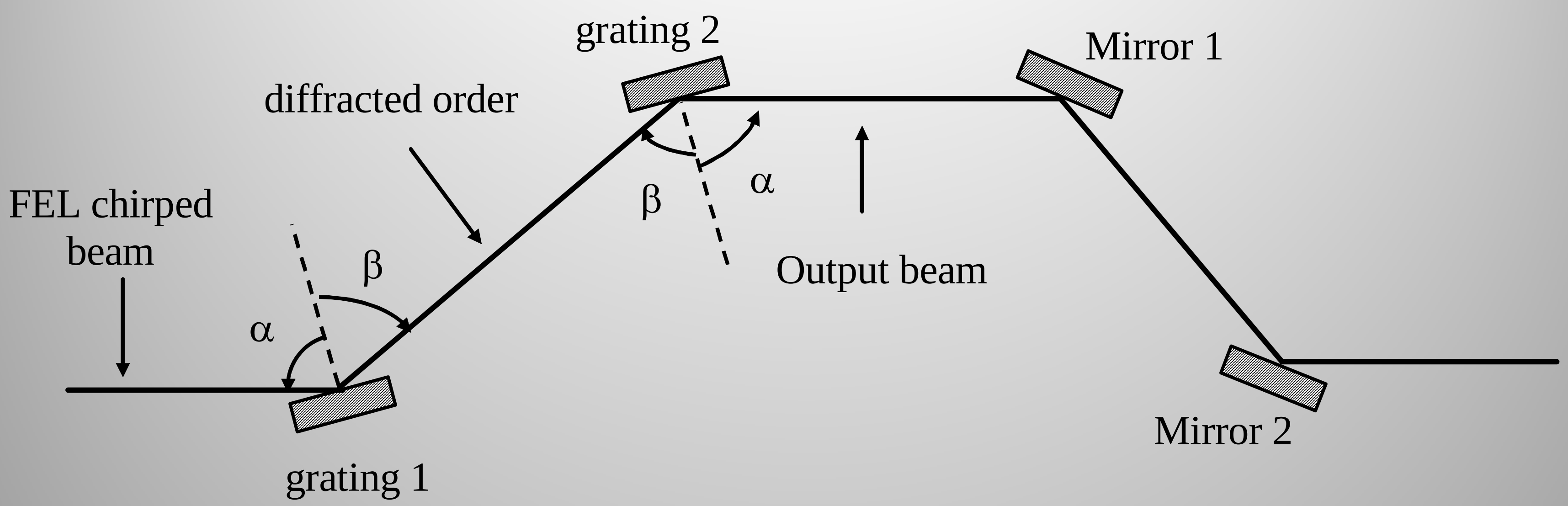
The compressor

The compressor



Compressor design

(by L. Poletto and F. Frassetto)

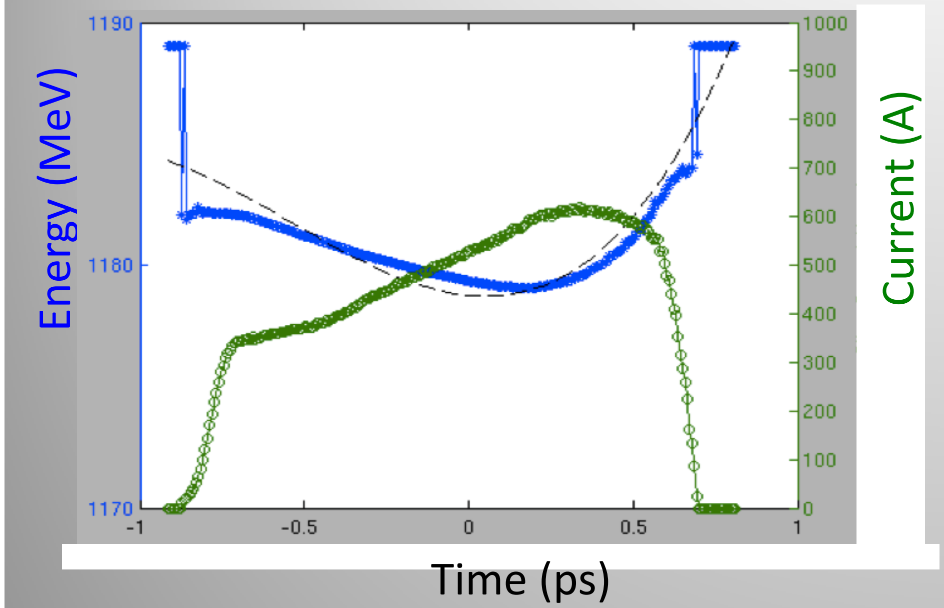


Spectral range	20-40 nm
Spectral bandwidth	0.02-0.015 nm
Temporal compensation	100-400 fs
Dimensions	<1.5 m
Measured efficiency	≈ 5%

Electron-beam, seed and FEL preparation

The electron beam and seed preparation

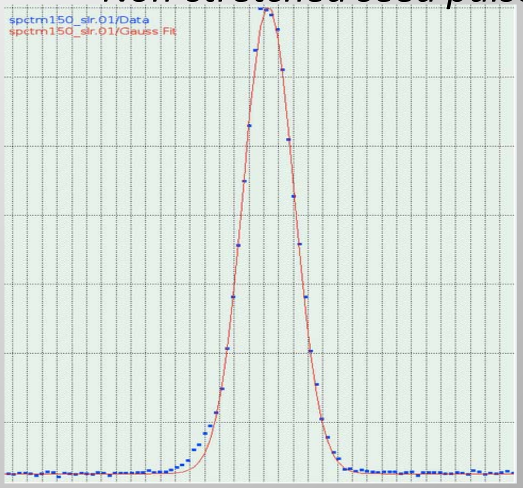
Control the Energy electrons Chirp $\lambda_{res} = \frac{\lambda_0}{2n\gamma^2}\left(1+\frac{K^2}{2}\right)$



Electron-beam parameters	
Bunch duration	1.3 ps
Peak current	400-600 A
Energy	1.18 GeV
Energy spread (slice)	150-200 KeV
Emittance (projected)	2.7/1.1 mm mrad
Quadratic energy chirp	few Mev/ps^2

Control the Seed stretching

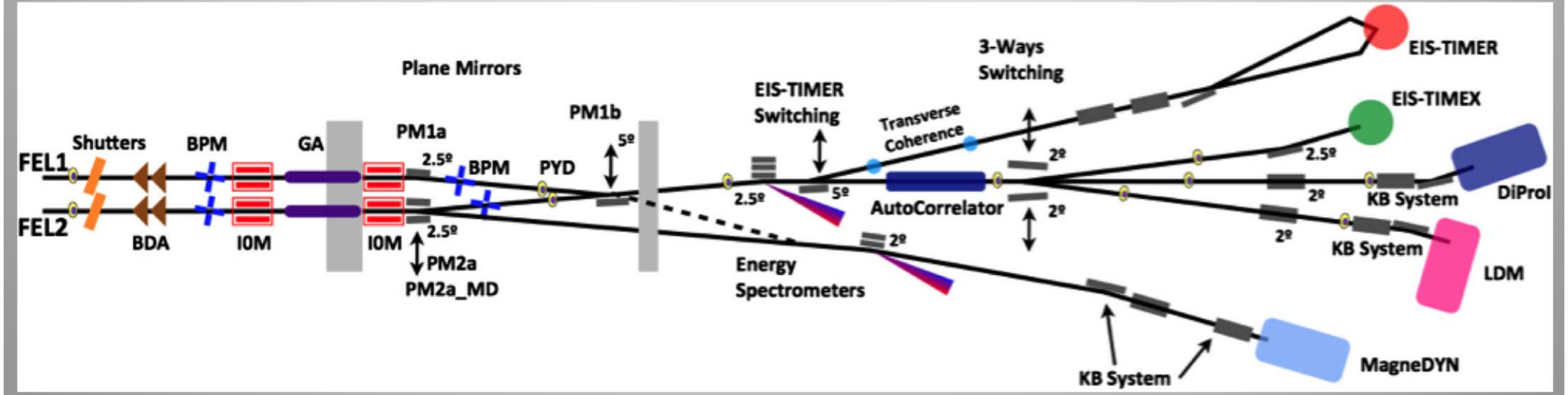
Non-stretched seed pulse



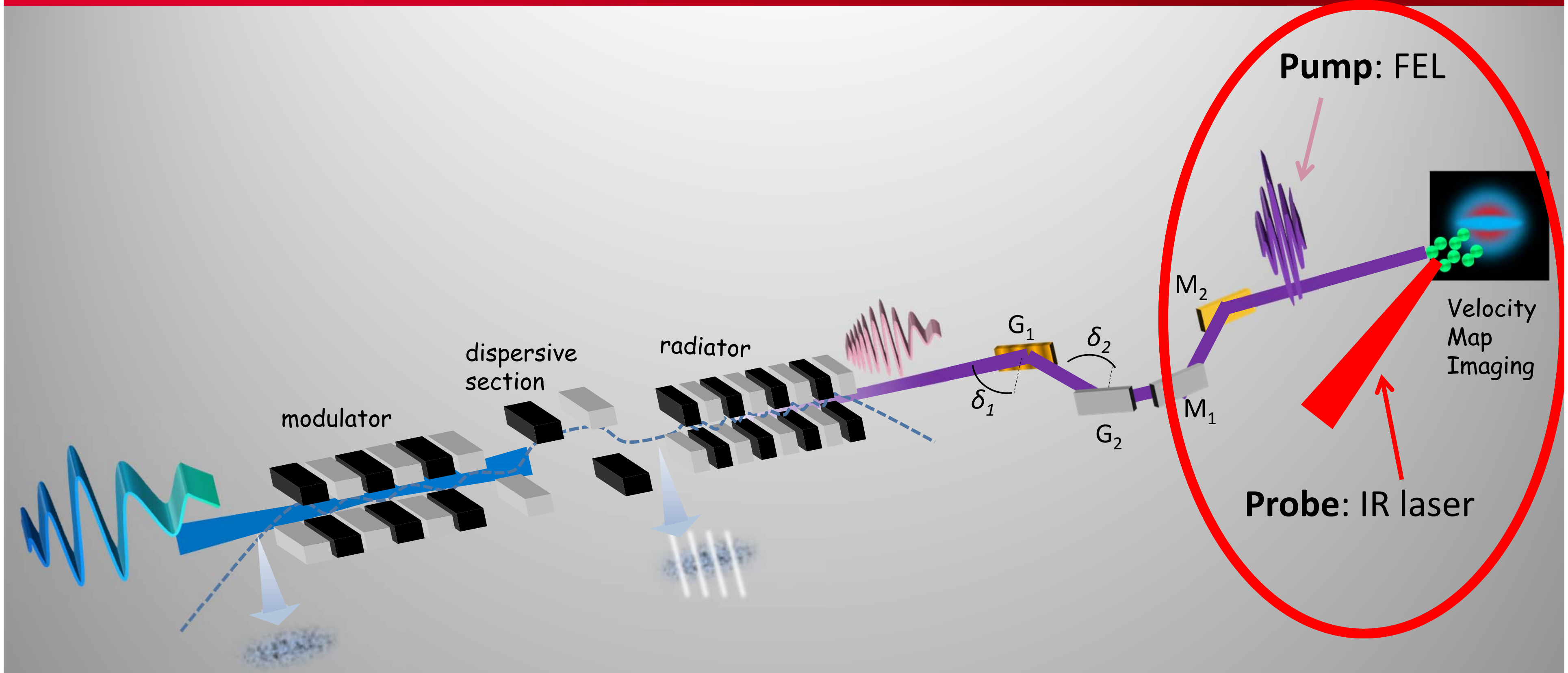
Seed parameters	
Wavelength	261 nm
Pulse duration (before stretching)	170 fs (FWHM)
Pulse duration (after stretching)	290 fs (FWHM)
Pulse bandwidth	0.7 nm
Power	100-200 MW

Measurement of FEL pulse duration: method and analysis

Measurement of pulse duration



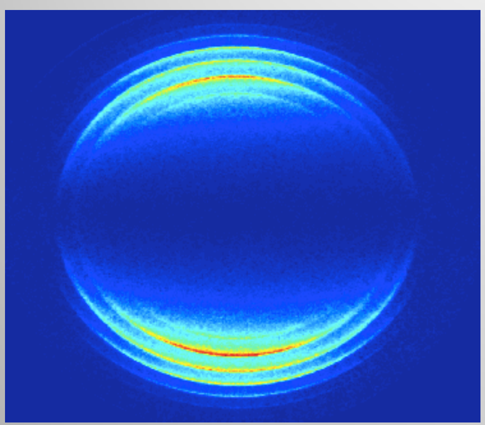
Measurement of pulse duration



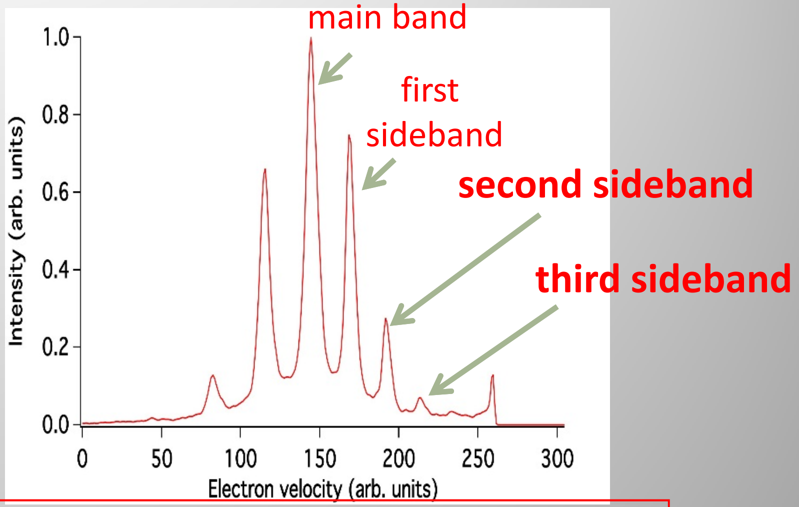
@Low Density Matter (LDM) Beamline

Measuring FEL pulse duration: method and analysis

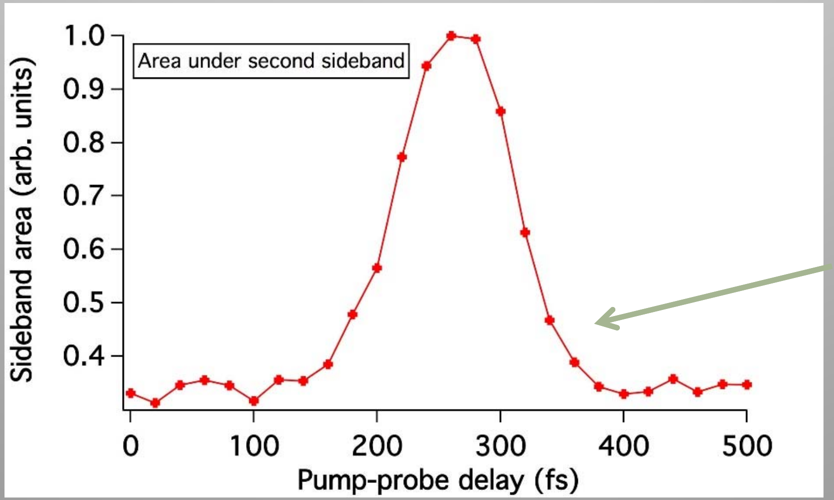
Photo-electron distribution



Energy spectrum



Cross-correlation curve by varying the pump-probe delay

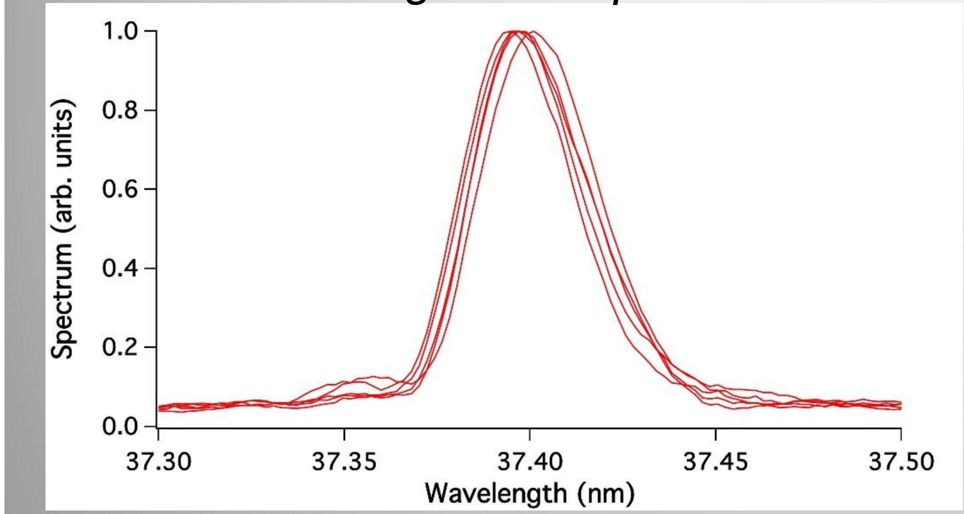


FEL pulse duration obtained by deconvolving the duration of the Laser seed pulse

Results of the CPA experiment

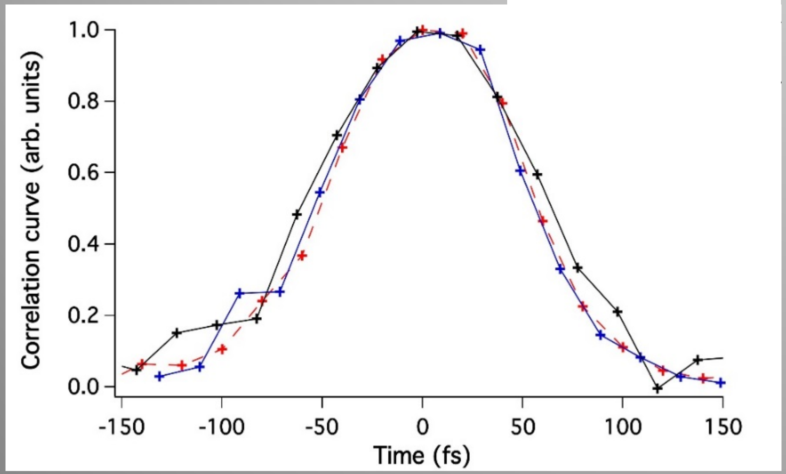
The initial FEL pulse (no seed stretching, no FEL compression)

Single-shot spectra



Average spectral width: 0.0384 nm

Cross-correlation curves



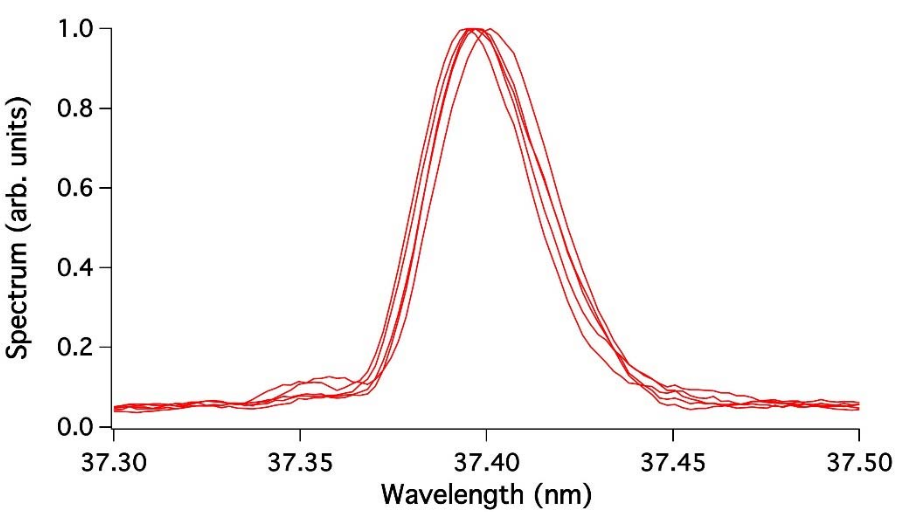
FEL pulse duration: 91 fs

Good agreement with expectations:
$(\sigma_t)_{seed}/n^{1/3}$ = 89 fs

Time-bandwidth product
factor 1.7 above transform limit

The stretched FEL pulse (no compression)

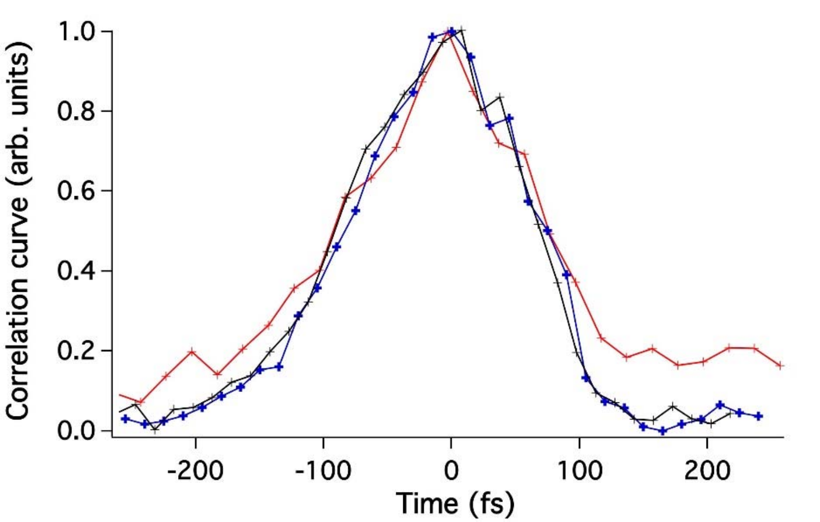
Single-shot spectra



Spectral width: 0.0446 nm

Fairly good agreement with the scaling law predicted by the CPA theory

Cross-correlation curves

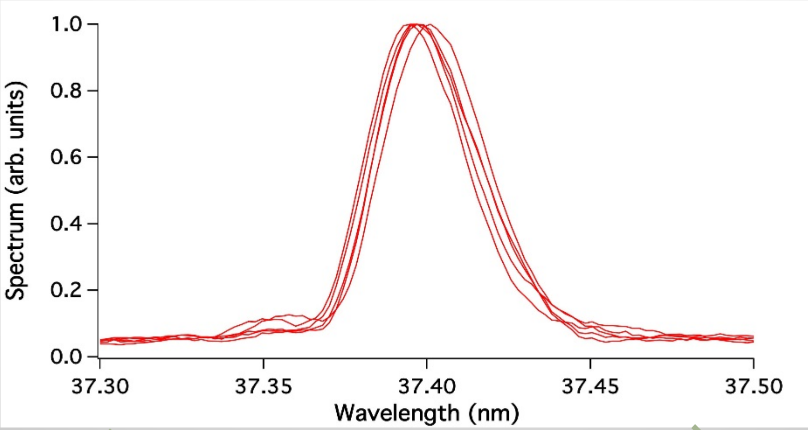


FEL pulse duration: 143 fs

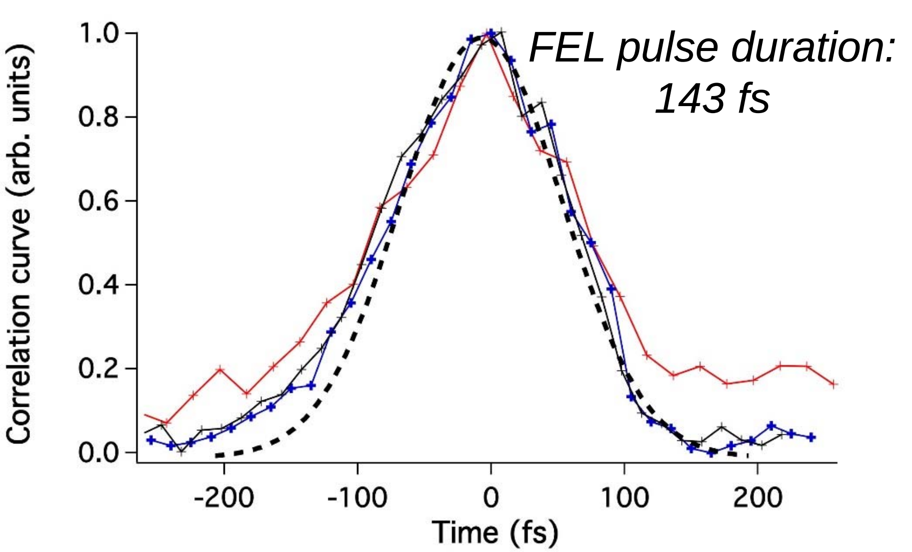
D. GARZELLA on behalf of the Sincrotrone Trieste and CEA/CNRS teams

NOCE2017 Workshop– Arcidosso, 19th - 22nd September, 2017

Compressed FEL pulse

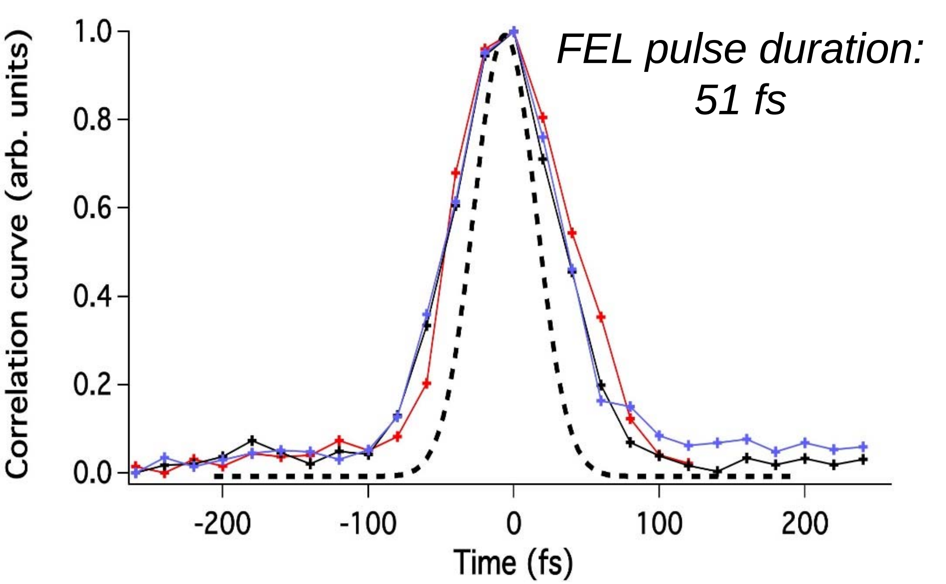


no compression



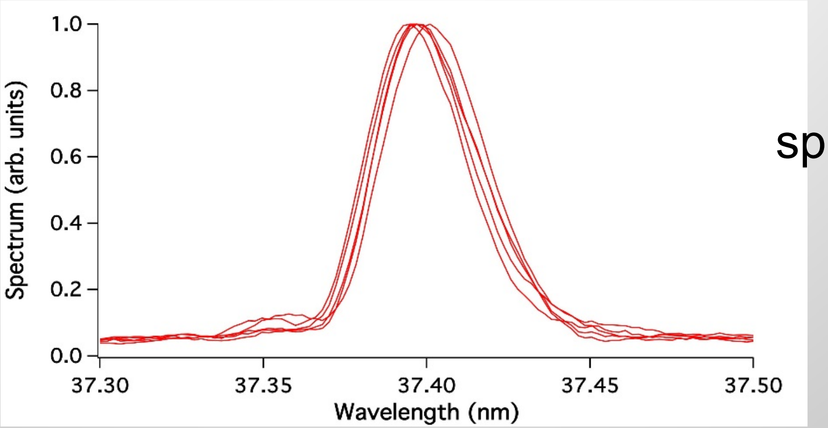
FEL pulse duration:
143 fs

compression



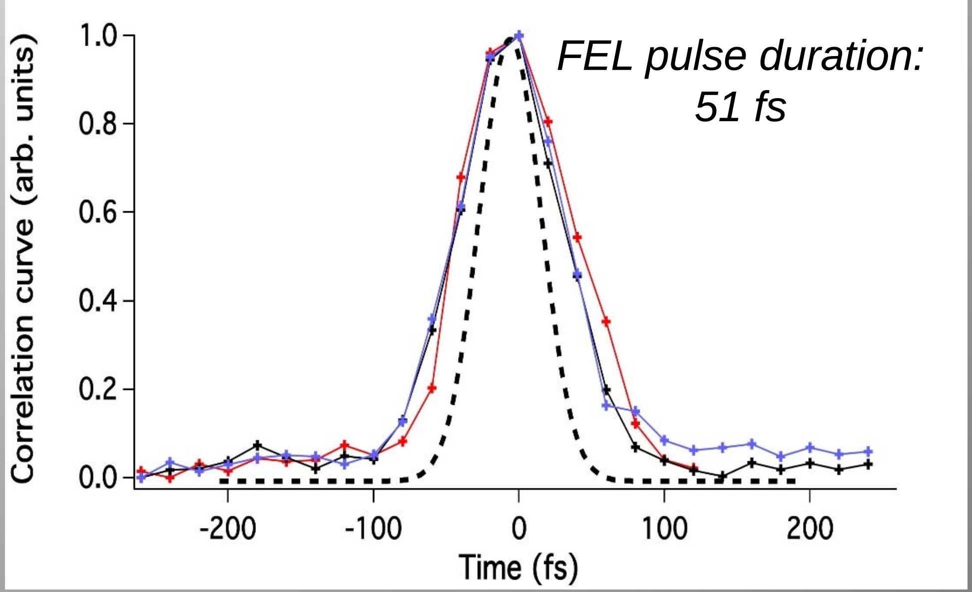
FEL pulse duration:
51 fs

Compressed FEL pulse



spectral width: 0.0446 nm

compression



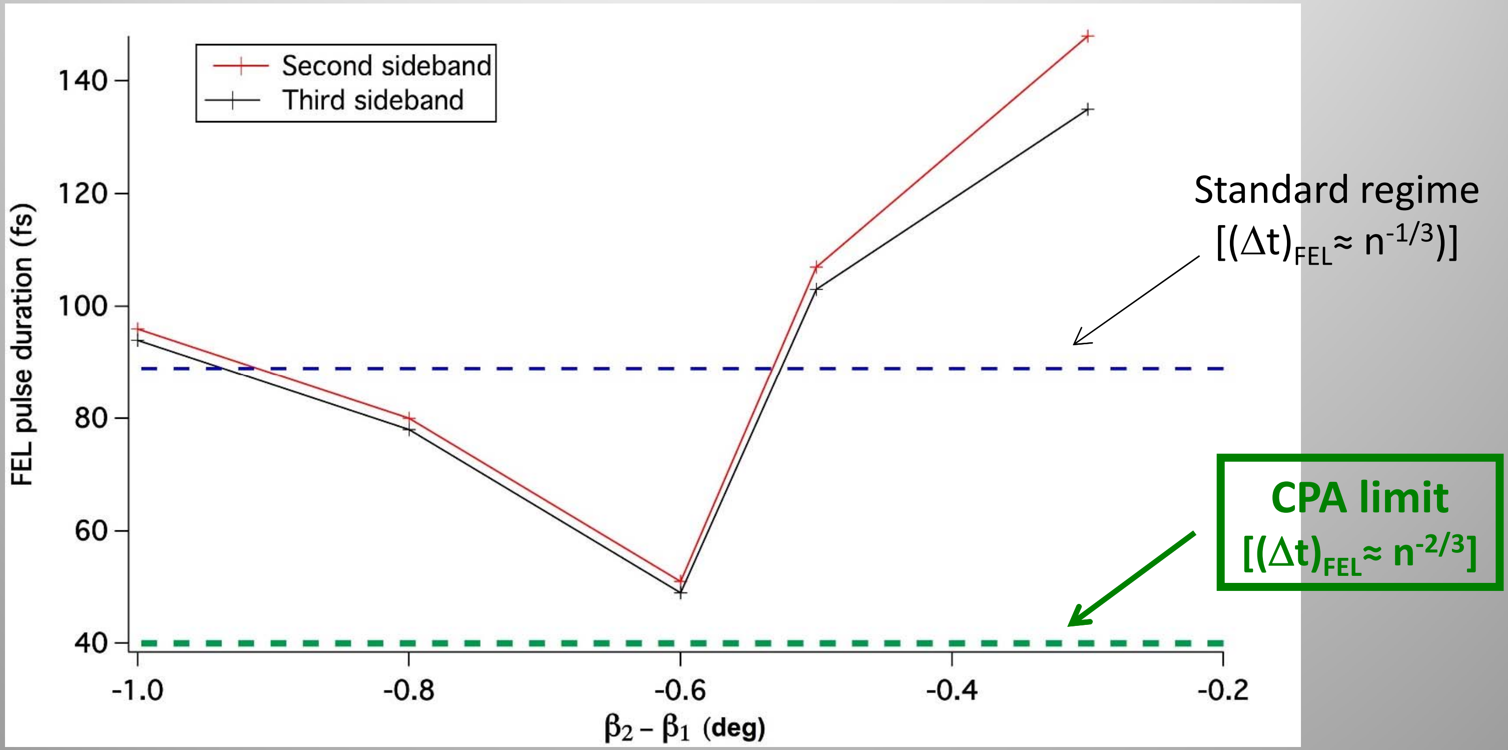
FEL pulse duration: 51 fs

Time-bandwidth product
factor 1.1 above transform limit

D. GARZELLA on behalf of the ELETTRA, CEA and CNRS teams

Compressor performance

Measured FEL pulse duration as a function of the difference between the incidence angles on the two gratings.



Standard regime
$[(\Delta t)_{FEL} \approx n^{-1/3})]$

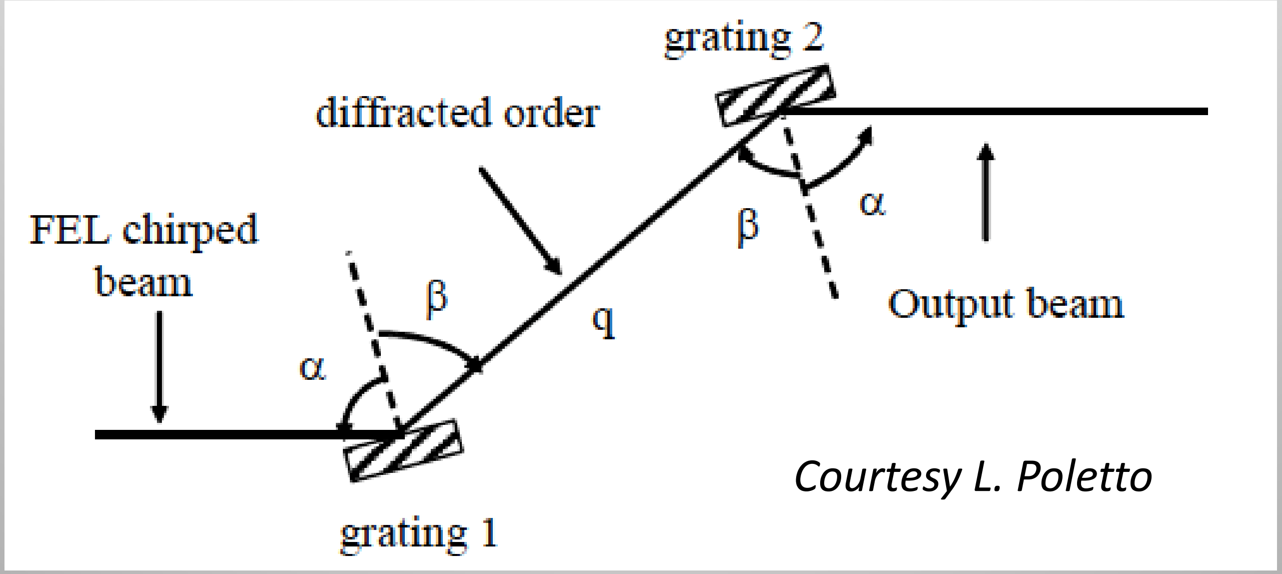
CPA limit
$[(\Delta t)_{FEL} \approx n^{-2/3}]$

The result obtained at maximum compression is close to the theoretical limit

D. Gauthier et al., Nature Communications,
vol. 7, (2016) p. 13688, doi :10.1038/ncomms13688(2016).

Next Step : CPA with FEL-2 @17 nm

Generation of few-fs pulses at 17 nm and below:Compressor

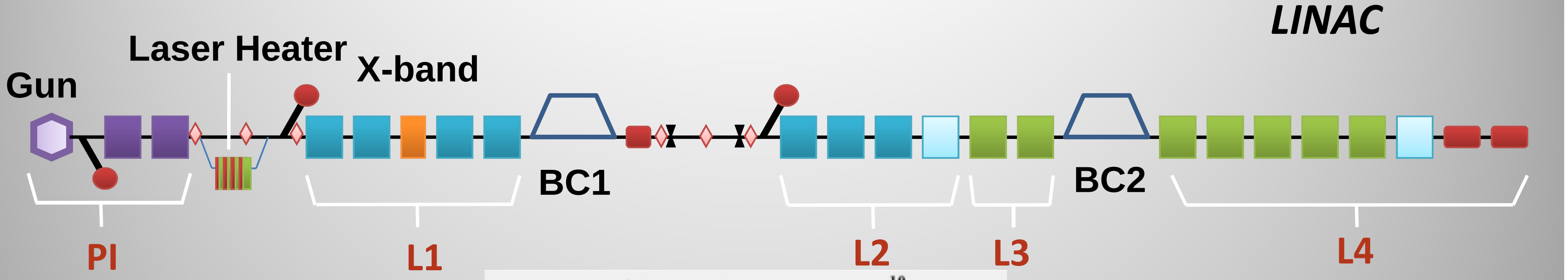


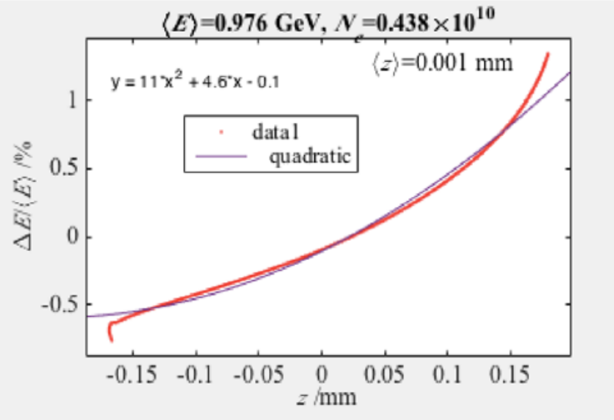
Courtesy L. Poletto

The compressor can be used down to 4 nm with different gratings and with minor changes to the mechanics.

The constraints on the available space at FERMI force the use of the gratings in the classical geometry, which has intrinsically a low efficiency (in the range of few %).

The electron beam and seed preparation @17 nm



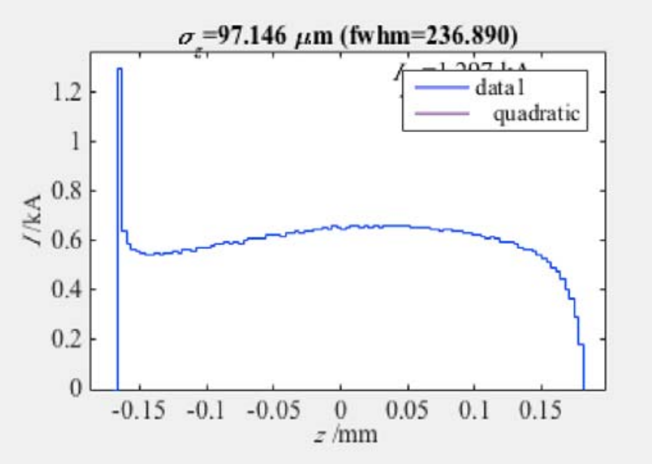


SETTINGS

- **Q=700pC**
- L01: -28.5deg
- X: 15MeV
- BC1: R56=-41mm
- L02: on-crest
- L03: -45deg
- L04: k10-12 at -50deg, k13-k15 -90deg

Lin chirp: 13.5 MeV/ps

Quadr chirp: 9.7 MeV/ps^2



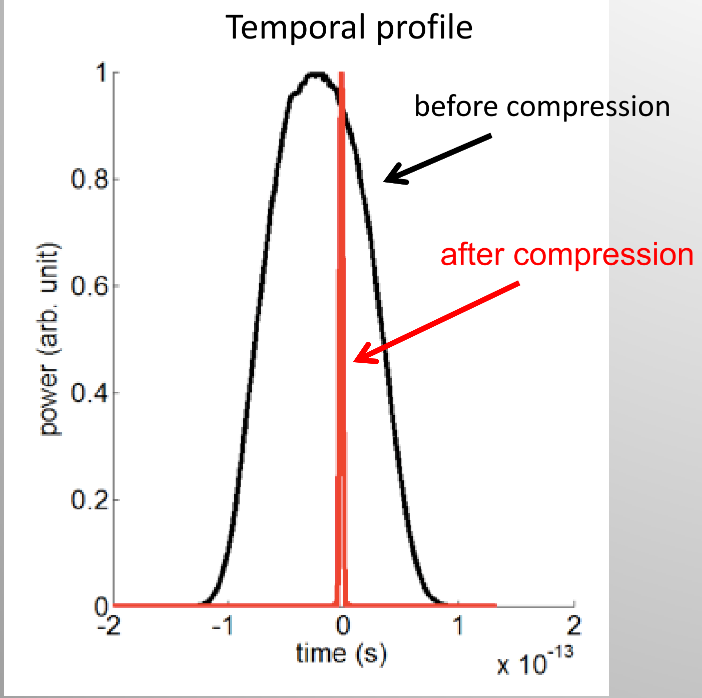
Courtesy G. Penco(numerical code: LiTrack)

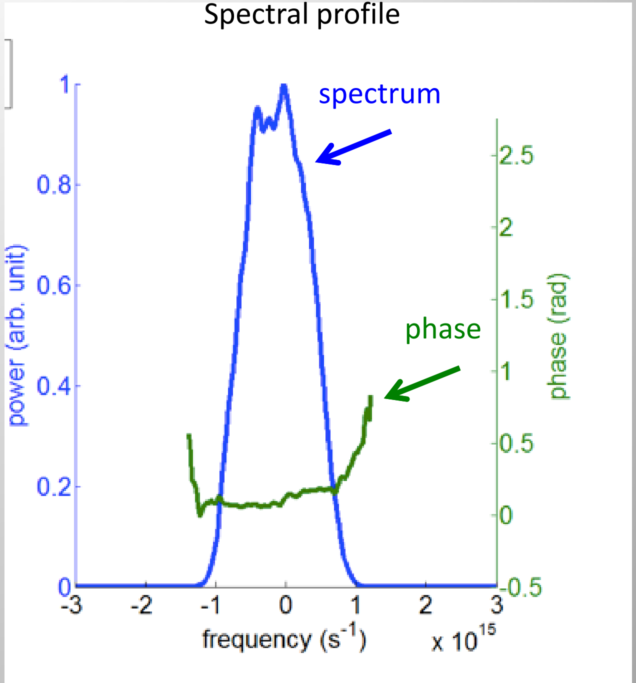
Few-fs pulses @17 nm :
Seed and Electron Beam

For the design of the experiment, we used both seed and electron-beam parameters already available at FERMI.

Beam and Laser Main Parameters			
Harmonic Number (n)	**FEL Wavelength**	**15 (5x3)**	**17.6 nm**
Seed Bandwidth	**Pulse Duration (Fourier Limited)**	**1.8 nm**	**55fs (FWHM)**
Duration Streched Seed	**Chirp rate**	**300 fs (FWHM)**	
Seed Power	**Laser Energy in the Modulator**	**450 MW**	**150 µJ**
Electron Beam Energy	**Beam Current**	**0.98 GeV**	**600 A**
Electrons Linear Chirp	**Electrons quadratic Chirp**	**13 MeV/ps**	**10 MeV/ps^2**

Few-fs pulses @17 nm : FEL Performances



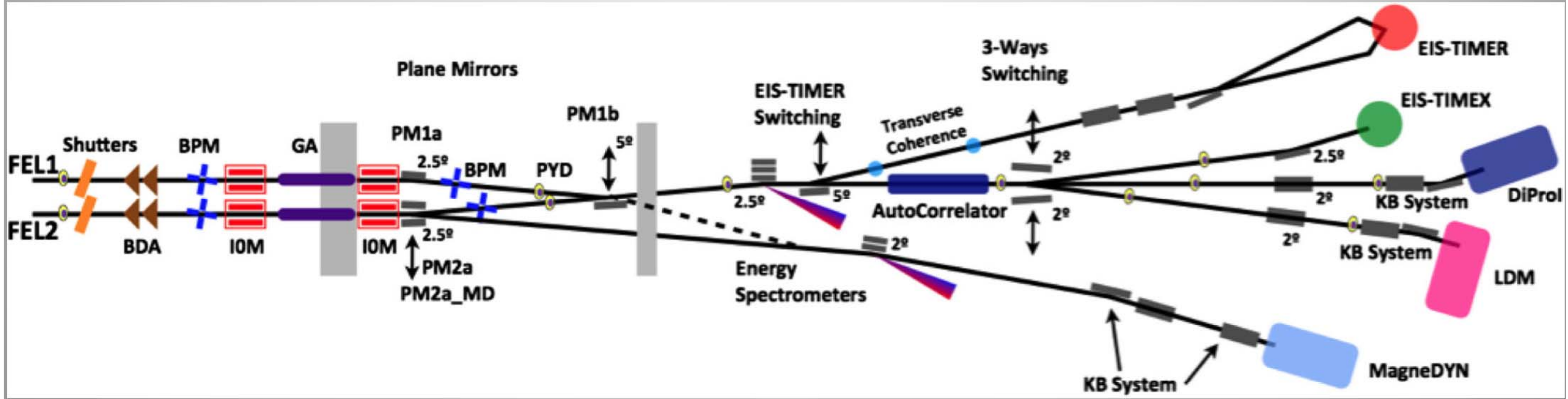


Courtesy D. Gauthier (numerical code: Perseo)

Expected FEL Performances			
FEL Output Bandwidth	**FEL Output Duration**	**2.5 *10^{14} rad/s**	**100 fs**
Compensated Group Delay Dispersion (β)		**400 rad/fs^2**	
Duration after Compression		**9 fs**	
Output FEL pulse Energy		**50 μJ**	
Estimated Peak Power vs. compressor Efficiency		**1%= 170 MW**	**5%= 850 MW**

Measuring Pulse duration : Mini-TIMER experiment

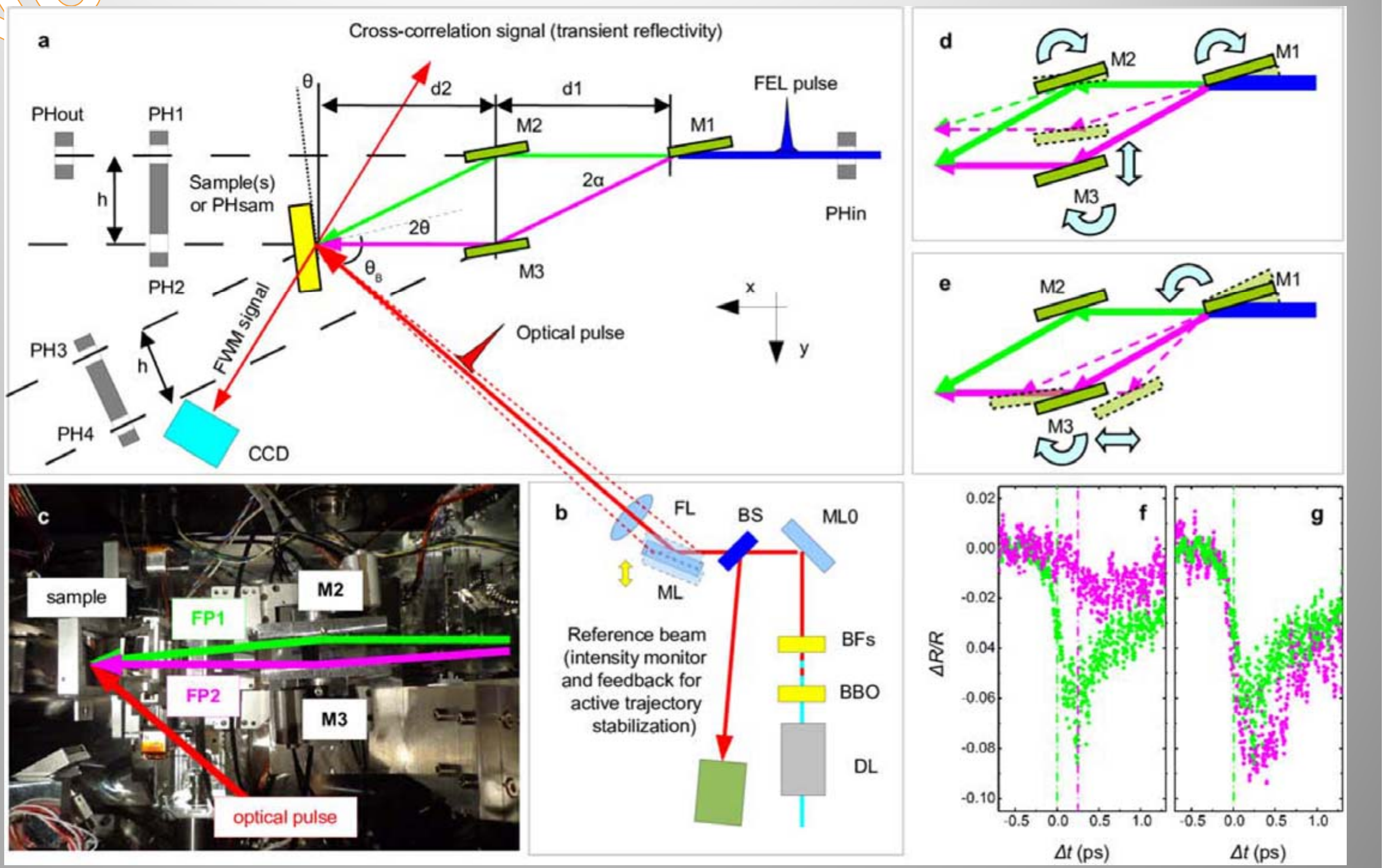
New !



Measuring Pulse duration : Mini-TIMER experiment

New !

Transient Grating approach



F. Bencivenga et al., Nature , 520, April 2015, 205

A list of possible issues

- -**High-order terms in the chirp** carried by the seed and/or in the electron beam energy distribution.

- **Systematic errors,** e.g., due to electron-beam phase-space curvature and/or non-homogeneous optics, may be compensated using a system (e.g., a deformable mirror) for active pulse shaping of the seed in a dispersive region.

- **Stochastic errors**, e.g., the ones due to the micro-bunching instability, will be more difficult to compensate. In order to mitigate the problem, we are working on the improvement of the quality of the photo-injector laser and will consider the possibility of operating the FEL at lower current.

- For extreme compressions, also the **jitter between the electrons and the seed** may play a role.

Conclusions and perspectives

We demonstrated the possibility to carry out chirped pulse amplification in seeded FELs.

The technique, which can be extended to FELs based on self-amplified spontaneous emission, **allowed us to achieve an unprecedented reduction of the FEL pulse duration**, with respect to the input seed.

The relatively large seed pulse duration, as well as the quite low transmission efficiency of the compressor, prevented the generation, after compression, of very powerful pulses. However, by shortening the seed pulse and improving the compressor efficiency (e.g., by adopting an off-plane mount geometry of the gratings), the potential is there to produce, with existing technology, coherent few-fs/sub-fs gigawatt laser pulses inside the water window.

As an example, starting with a 10-fs seed pulse at 260 nm and tuning the FEL radiator at 4 nm (n=65), CPA would allow to generate a few-GW pulse of about 600 as.

The CPA collaboration

The FERMI CPA collaboration includes:

- ✓ the following members of the FERMI team: E. Allaria, C. Callegari, C. Coreno, I. Cudin, M.B. Danailov, A. Demidovich, G. De Ninno, S. Di Mitri, B. Diviacco, E. Ferrari, P. Finetti, D. Gauthier, L. Giannessi, N. Mahne, G. Penco, L. Raimondi, P. Rebernik, R. Richter, E. Roussel, L. Sturari, C. Svetina, M. Trovò, M. Zangrando
- ✓ The CNR of Padova (Italy): F. Frassetto, P. Miotti, L. Poletto
- ✓ The LOA of Palaiseau (France): H. Dacasa, B. Mahieu, P. Zeitoun
- ✓ The CEA of Saclay (France): D. Garzella
- ✓ The IPFN of Lisbon (Portugal): M. Fajardo, S. Kunzel
- ✓ The European XFEL (Germany): M. Meyer, T. Mazza
- ✓ ISMO Connection in progress with The CNRS-ISMO : A. Klisnick, A. Le Marec