Investigation of pulse duration reduction and intensity increase of Petawatt-class laser systems

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UNIVERSITATEA DIN BUCUREȘTI

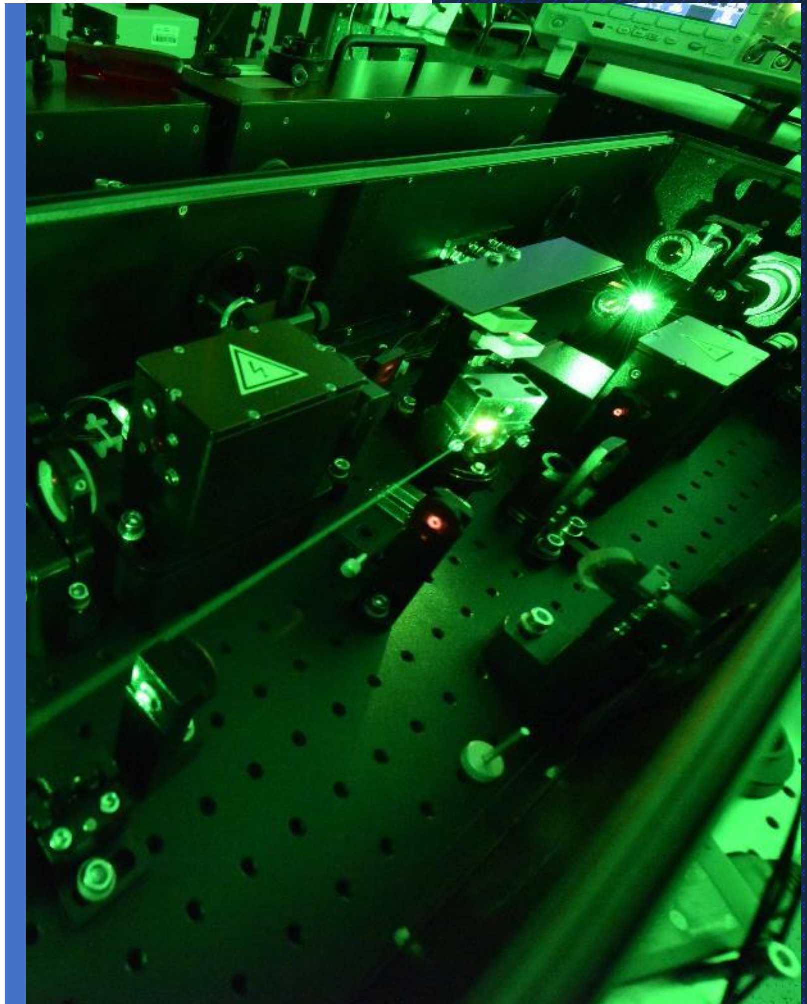
VIRTUTE ET SAPIENTIA

INSTITUT POLYTECHNIQUE DE PARIS

30.01.2024

The journey of this presentation.

- Motivation
- Post-compression experimental campaigns
- Post-compression at ELI-NP
- Conclusion and perspectives



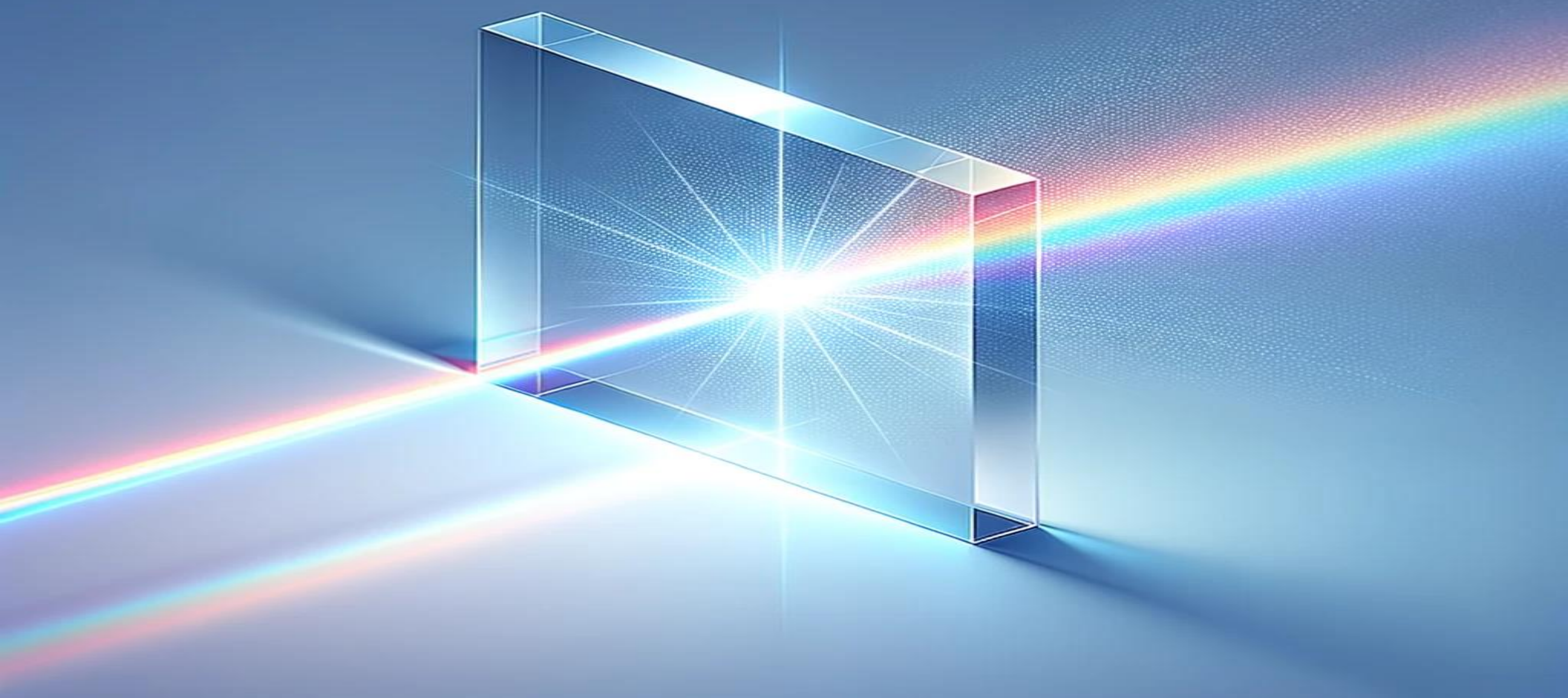
10 PW at ELI-NP

Beyond 10 PW class lasers…

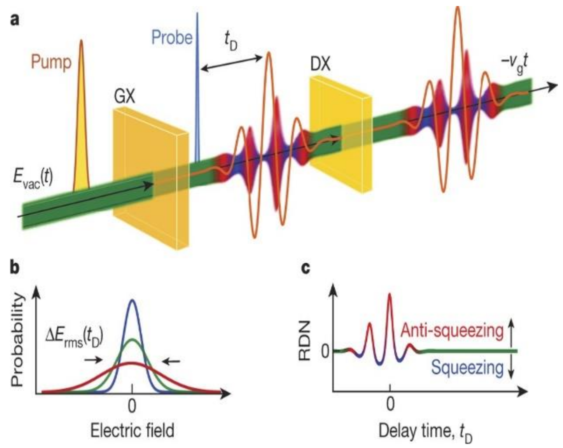
Exawatt class

Applications

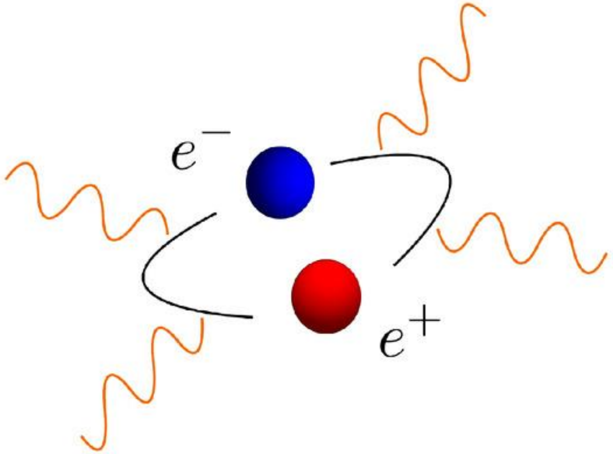
Following the “Passion for extreme light”



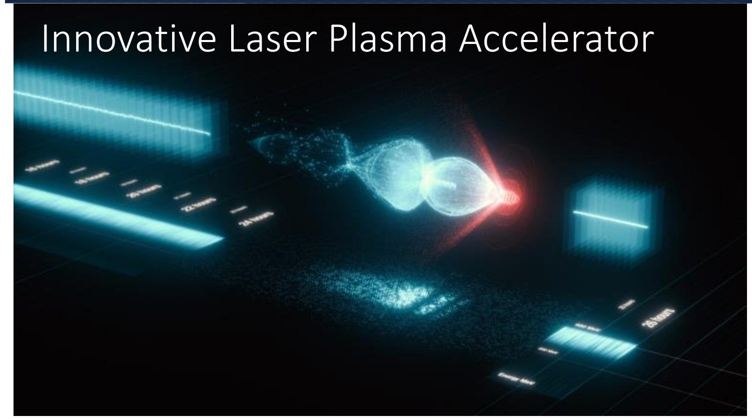
Motivation: intense, short pulses for experiments

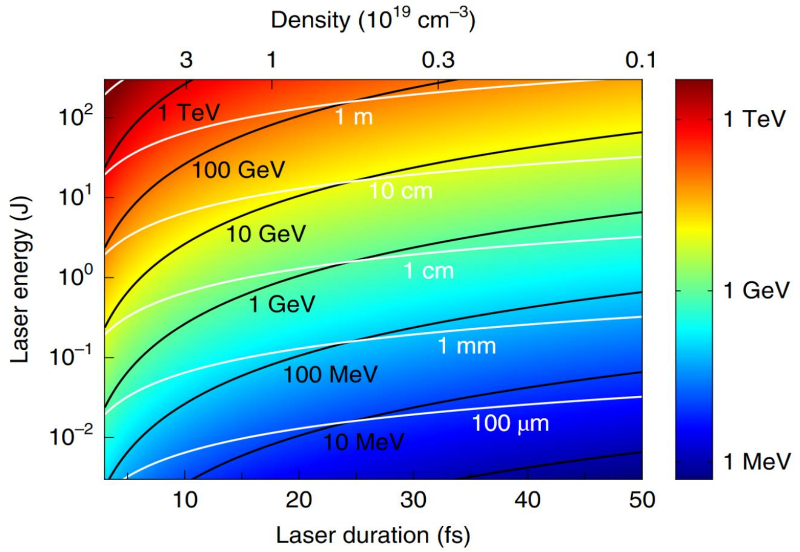


Riek *et al.*, Subcycle quantum electrodynamics, Nature, **541**, 376-379, 2017



Karbstein *et al.*, Probing Vacuum Polarization Effects with High-Intensity Lasers, Particles, ***3*(1)**, 39-61, 2020



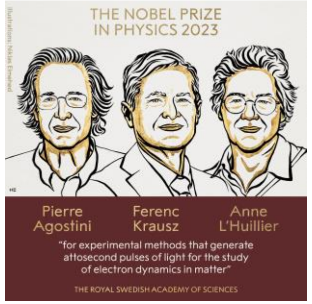


Evolution of energy gain with accelerator, laser and plasma parameters.

Caizergues *et al.*, Nature Photonics, **14**, 2020

Experiments requirements:

- **Intense laser pulses**
- ***Shortest pulse duration***
- ***High energy***
- ***Focusability***



Nobel 2023

Nobel 2018

Post-compression principle

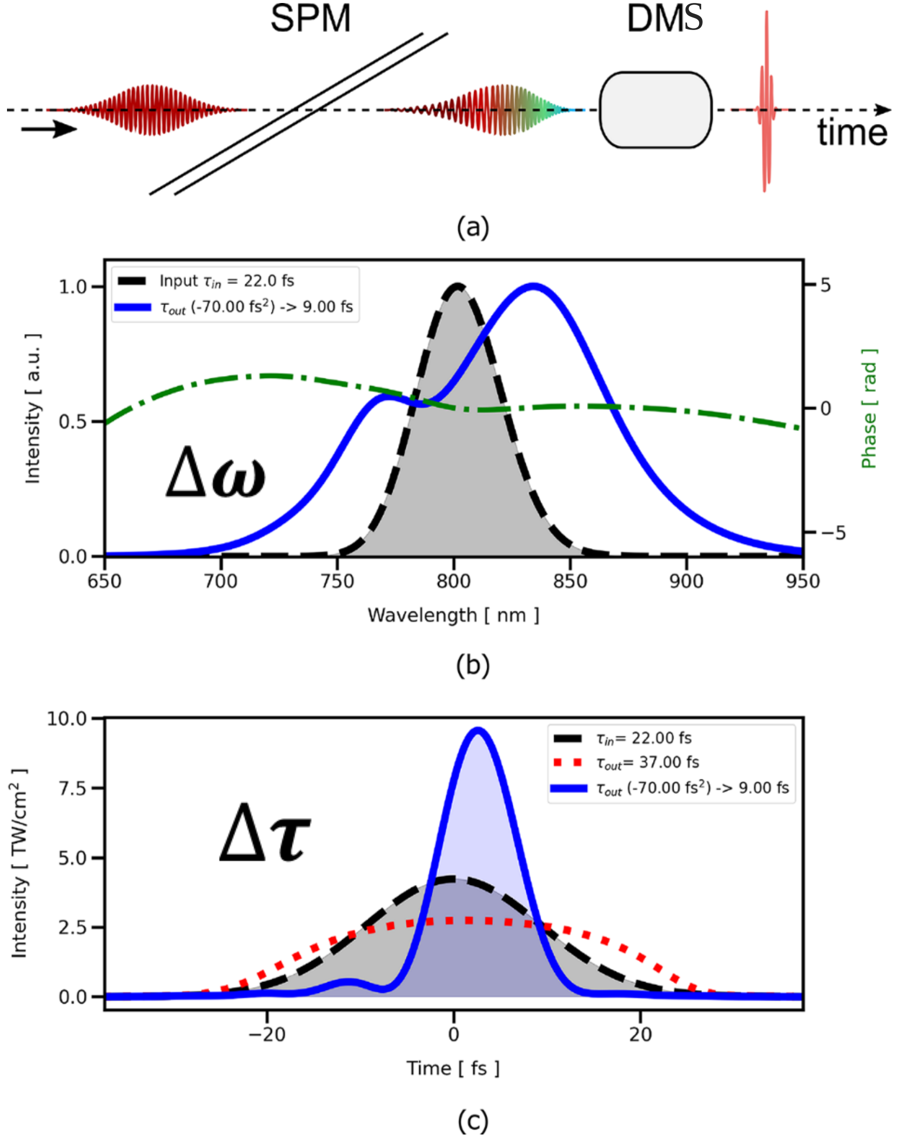


Fig. 1. Post-compression using spectral broadening

Self phase modulation (SPM)

+

Dispersion management System (DMS)

Fourier Limit

$$\Delta\omega * \Delta\tau = k$$

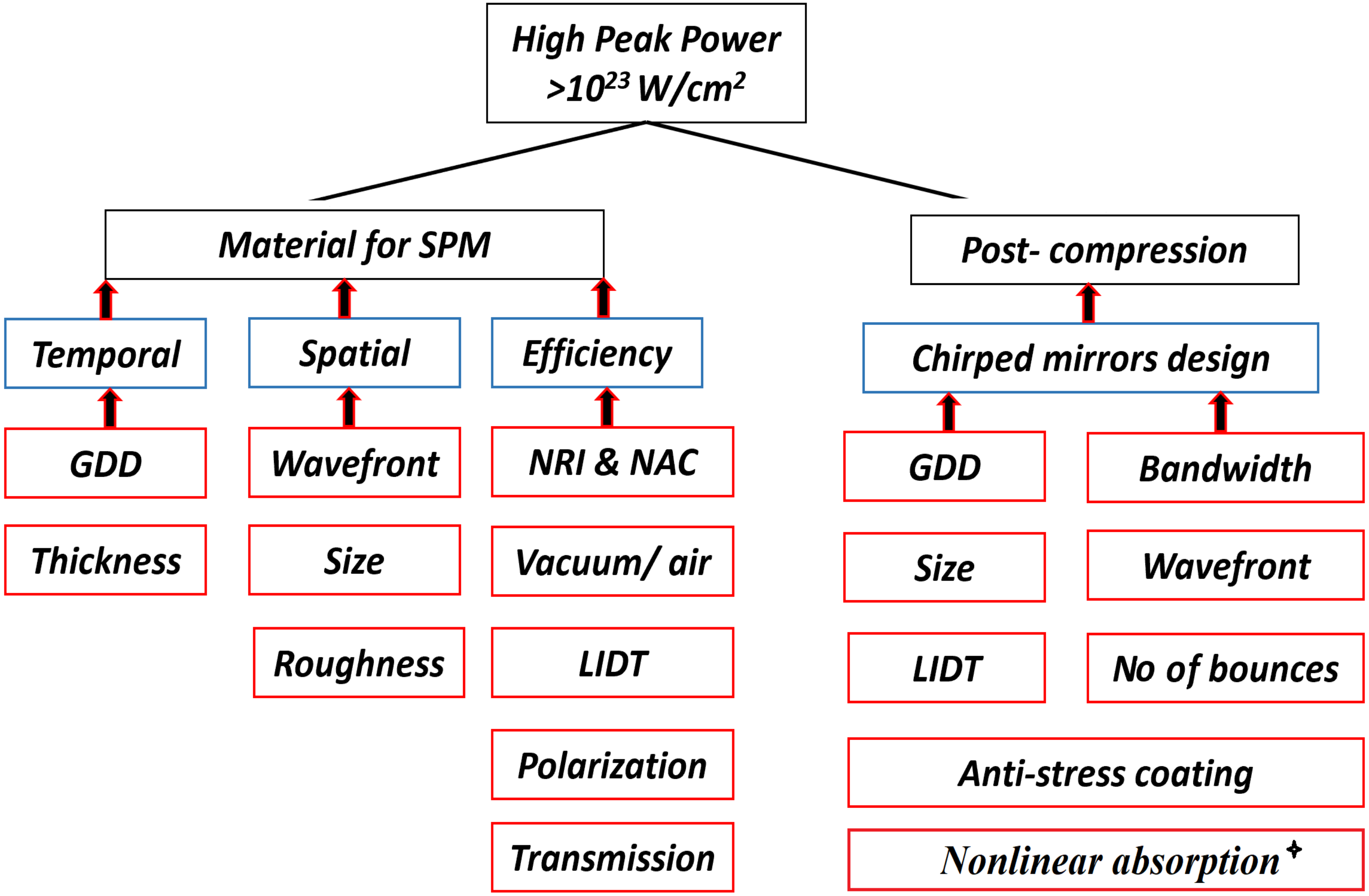
Requirement: Spectral phase=constant

Proposed SOLUTION:

Spectral broadening + spectral phase control

Bleotu *et. al*, HPLSE, **10**, 2022

Required optical components properties



Measurements performed:
- ✓ Materials characterization
- ✓ Non-linear refractive index
- ✓ Laser induced damage threshold (LIDT)
- ✓ Chirped mirrors characterization

Fig. 2. The main optical properties investigated in this thesis

✦ denotes a recent investigated property

Previous state of the art

Record at PW scale

11+- 1.5 fs

-large B integral studies
-assumed TOD=0

TOD- Third order of dispersion

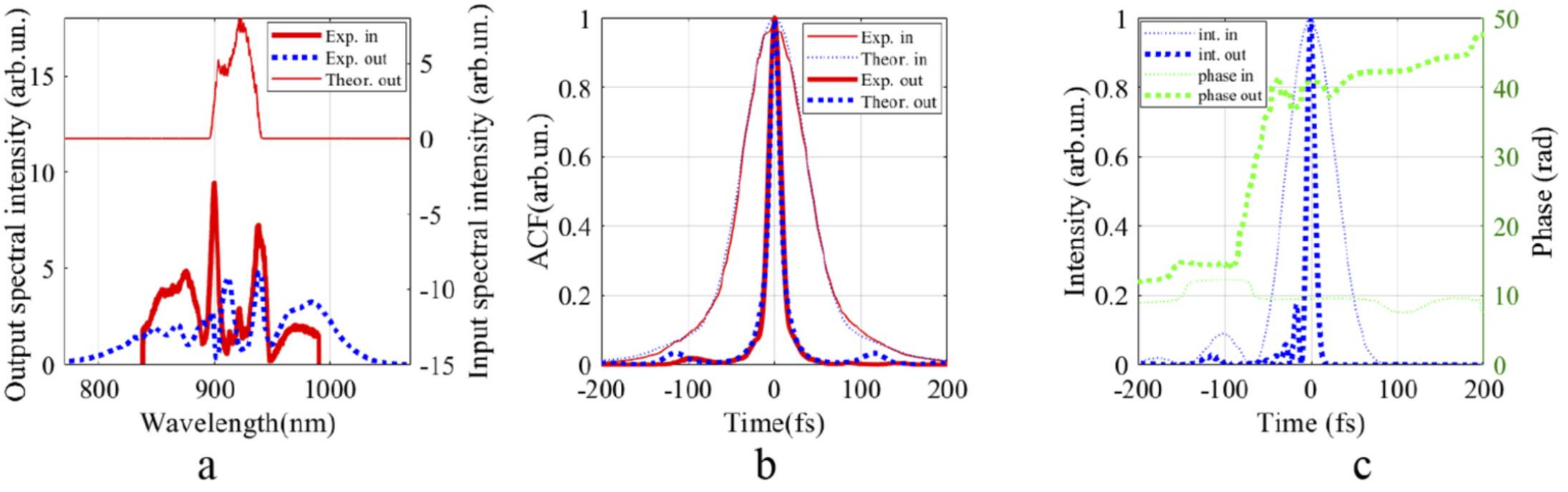


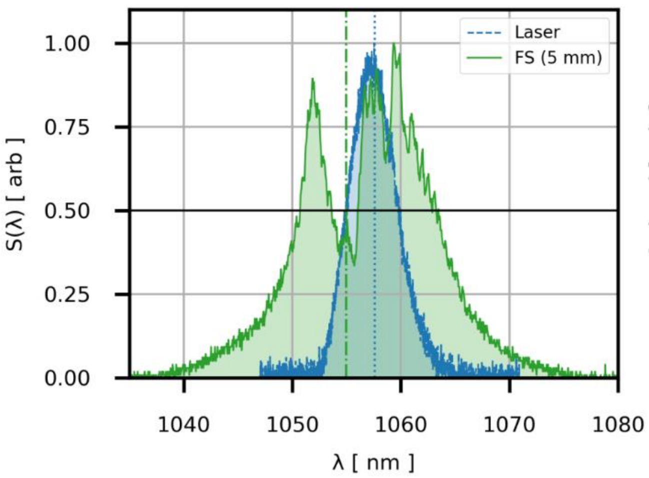
Fig. 2. (a) Spectra, (b) ACFs, and (c) pulse shapes at the input (thin curves) and output (bold curves) of the CafCA system: experimental (solid red curves) and theoretical (dotted blue and green curves). Parameters of the pulses are shown in Table 1 (B=13). The spectrum of the input pulse has sharp tails due to strong nonlinearity of parametric amplification in the laser PEARL. The spectrum of the output pulse, on the contrary, is limited by the bandwidth of the used spectrometer (840. . . 990 nm).

Figure extracted from:

Ginzburg, V., Yakovlev, I., Kochetkov, A., Kuzmin, A., Mironov, S., Shaikin, I., Shaykin, A., Khazanov, E., 2021. 10 fs, 1.5 PW laser with nonlinear pulse compression. Opt. Express 29, 28297. https://doi.org/10.1364/OE.434216

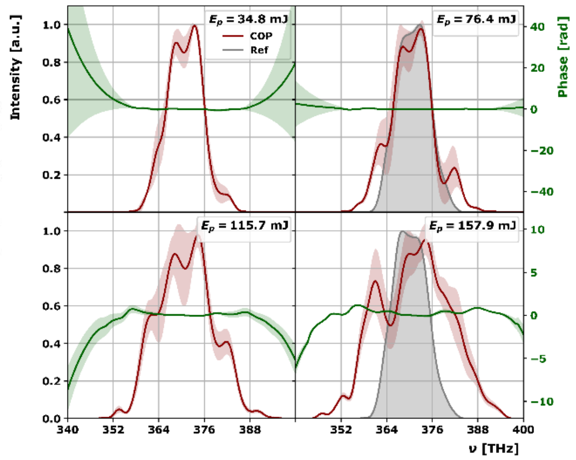
- ✓ No statistic, no TOD
- ✓ Single shot analysis

Further data analysis for post-compression experiments



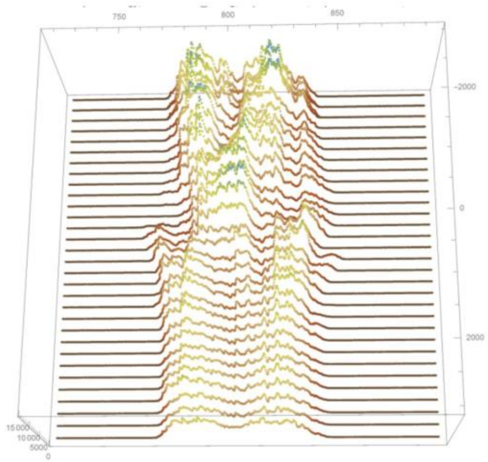
From **350- 124** fs @ ELFIE
Glass and plastics
No DM, No Dazzler

Bleotu et. al, HPLSE, **11**, 2022



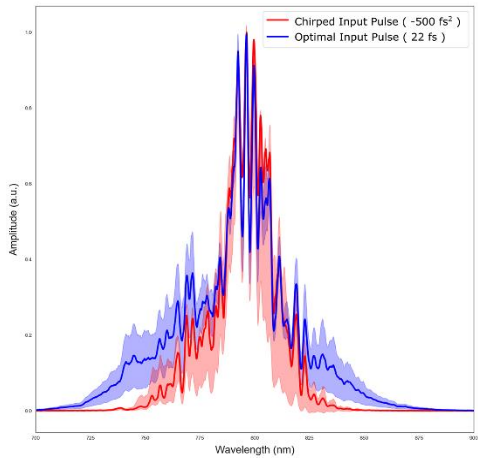
From **45-23** fs @ LASERIX ,50 TW
Plastics
No DM, Dazzler

Wheeler, **Bleotu** et. al, MDPI, **9**, 2022



From **24-20** fs @ ELI-NP, 100TW
Plastics and glass
No DM, Dazzler

Ursescu,… **Bleotu** et. al, Frontier in optics, 2, 2020



From **22-12** fs @
Apollon 1PW
Glass,
No DM, Dazzler

Bleotu et. al, HPLSE, **10**, 2022

Fig. 3. Work performed for 4 experimental campaigns

Key aspects:

- *Input laser parameters*
- *Type of the material, quality and LIDT*
- ***Dazzler and Deformable mirror (DM)***
- ***Chirped mirrors size (sub aperture post-compression)***

Experiments for spectral broadening

- ✓ **ELFIE; LASERIX; APOLLON; ELI-NP**
- ➢ **Focus quality**
- ➢ **Simulations for spectral broadening**
- ➢ **Pulse duration estimation**

Experimental Setup, E4, 100 TW

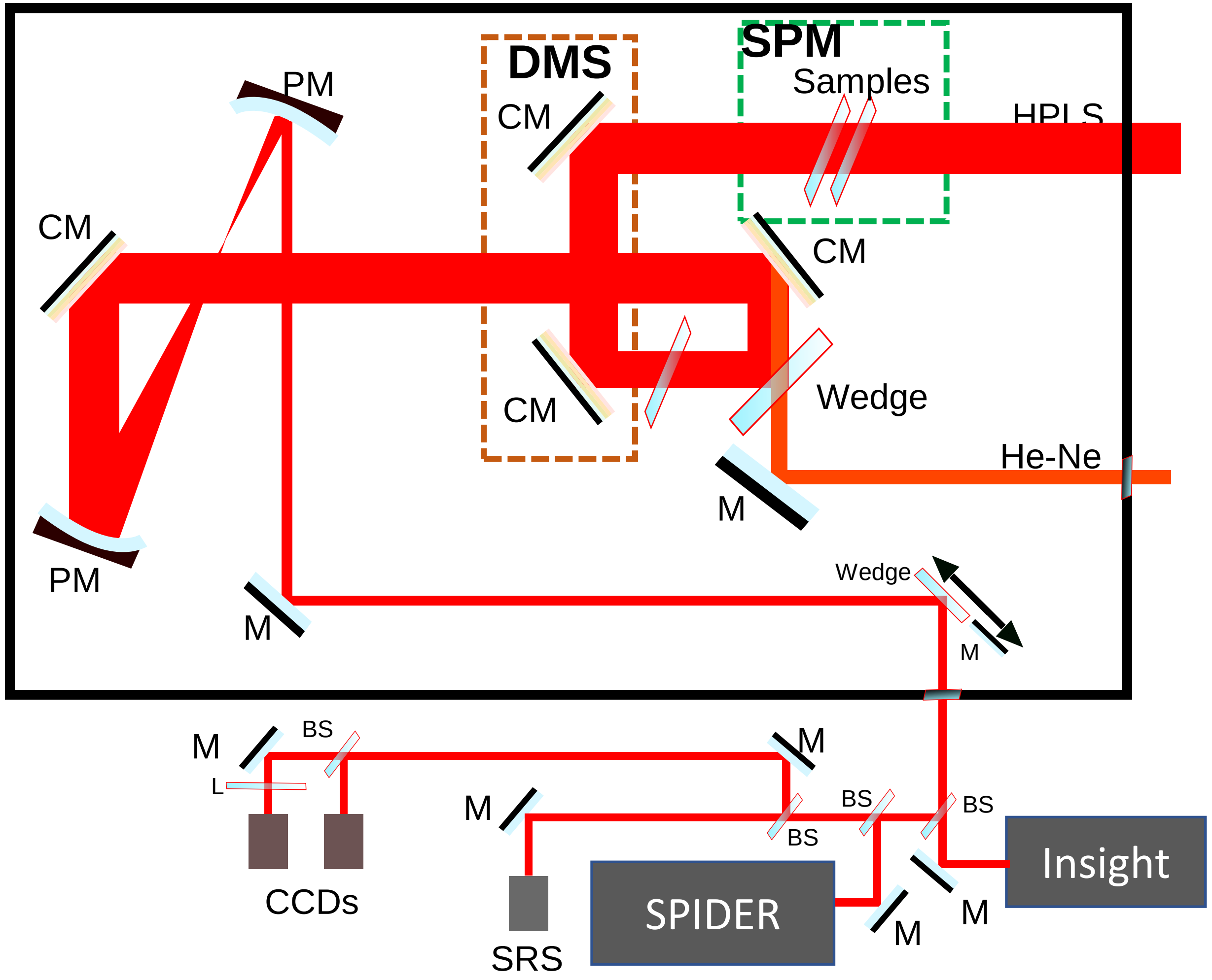
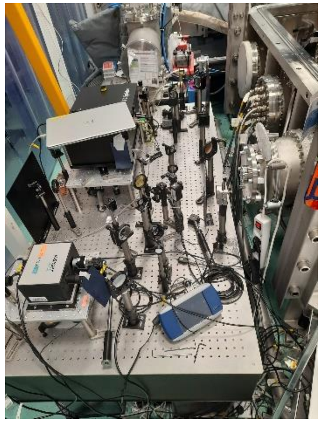


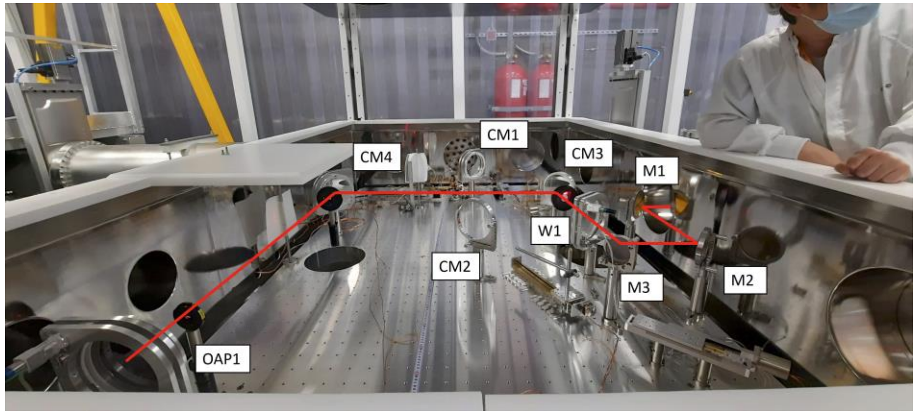
Fig. 4. Experimental setup used in E4, 100 TW.

where: PM-parabolic mirror, CM-chirped mirrors, M-mirror, BS-Beam splitter, L-lens, SRS- Spatially Resolved Spectrometer

Samples:

- **BK7 (1&2 mm)**
- **FS (5mm)**
- SF5 (1 mm)
- **SF5+BK7 (1 mm + 1 mm)**
- Zeonor (0.1 mm)





1J pulses post-compressed
@11.36 +/- 0.4 fs
Full aperture metrology

Metrology: Spectrum, Phase, Duration

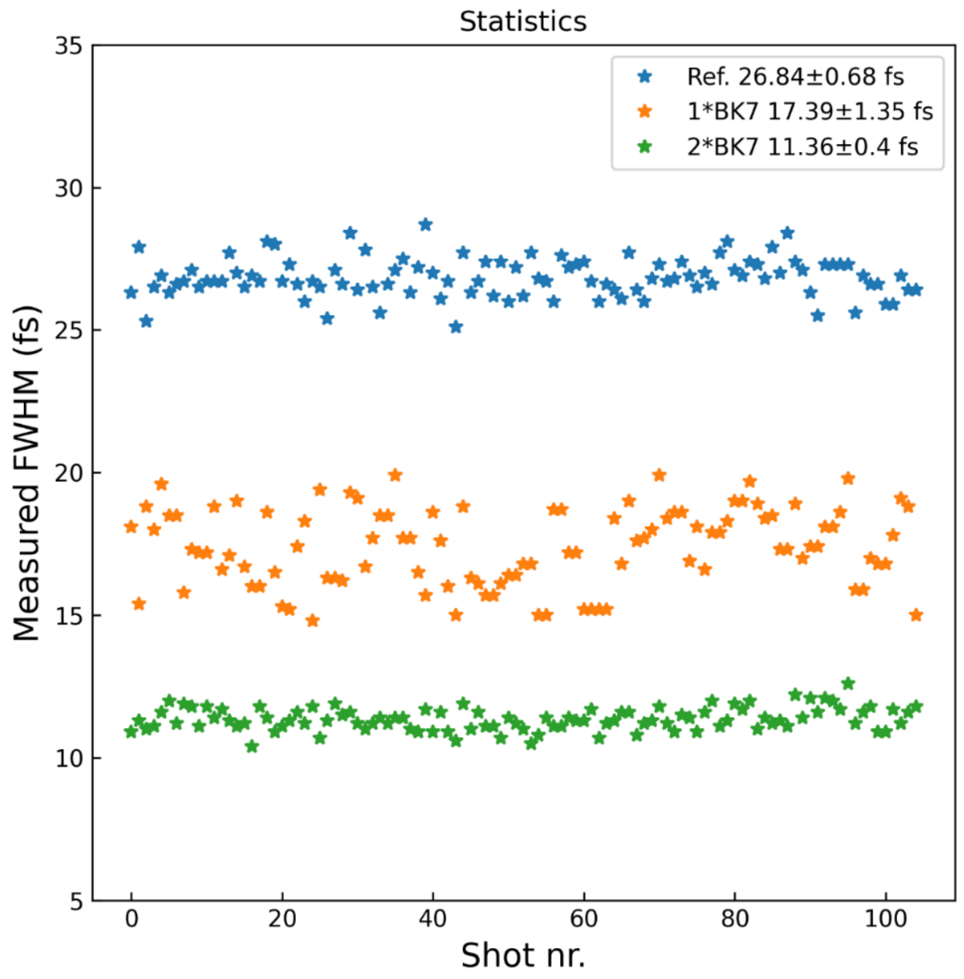


Fig. 5. Stability –Statistics of the MEASURED pulse duration after GDD and TOD Dazzler corrections

Temporal metrology:
- ✓ ***close to FTL***
- ✓ ***stable post-compressed pulses***
- ✓ ***Temporal Strehl Ratio (TSR)***

GDD – Group delay dispersion, TOD - Third order of dispersion

Metrology: Spatial results: material wavefront distortion

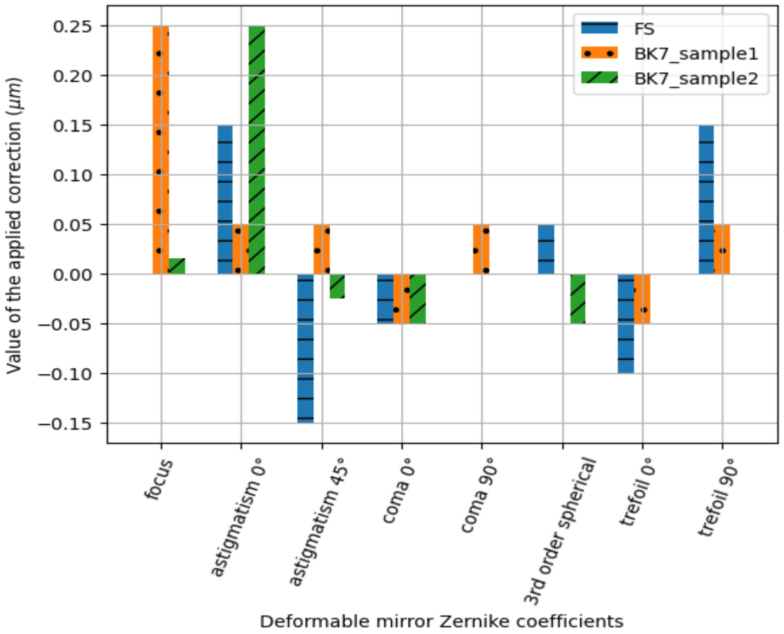


Fig. 6. DM low energy Zernike coefficients correction

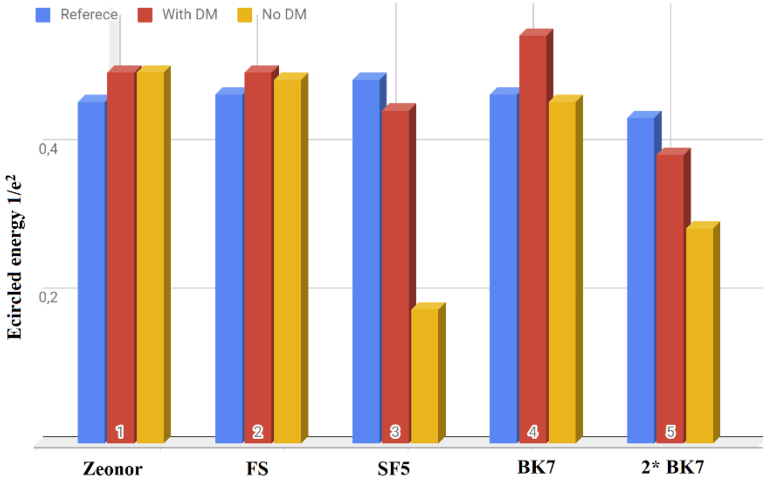


Fig. 7. Focal spot improvement using DM at low energy

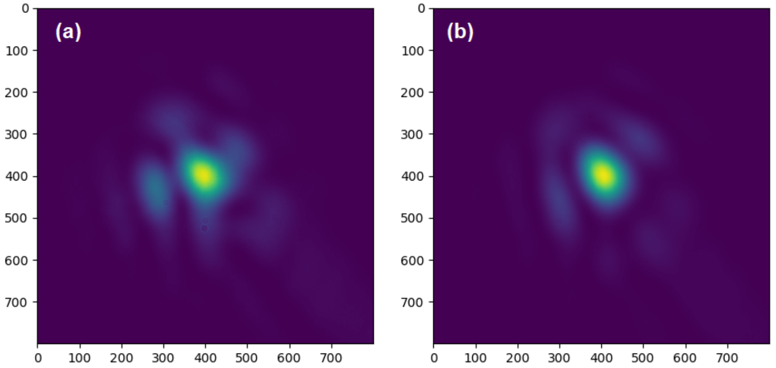


Fig. 8. FF images without (Left) and with (Right) DM correction for BK7

Characterization of focusability using DM:

- ✓ ***Linear (material) -> compensated with DM***

Courtesy of S. Popa, M. Talposi, D. Matei

Spectral broadening scaling

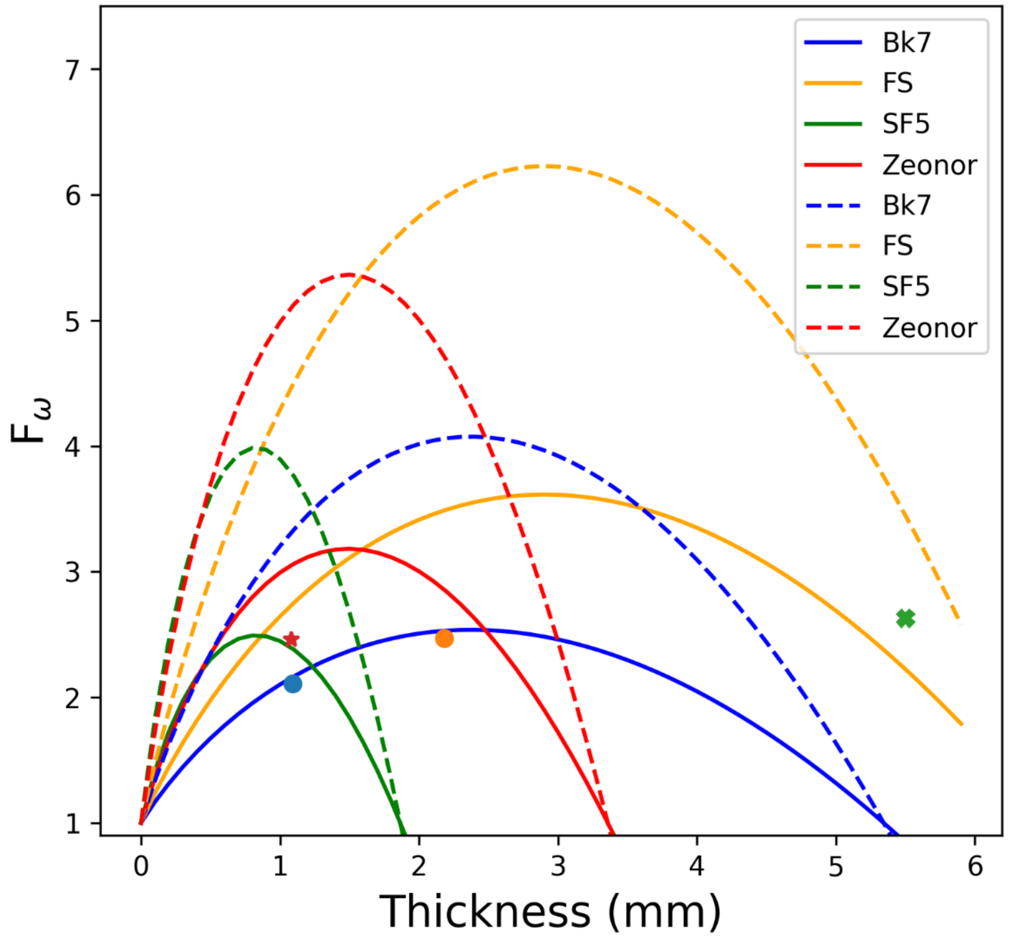


Fig. 9. Measured and estimated broadening @ 1 J (line) and 2 J (dashed)

$$F_\omega = 1 + g_\omega B(1 - h_\omega \sqrt{D})$$

Estimated spectral broadening
B: B- integral
D: dispersion parameter = L*GDD/t^2
-> for 1 J (continuous curve)
-> for 2 J (dotted curve)
o BK7 (measured)
***** SF5 (measured)
x FS (measured)

Broadening benchmarking and scaling

- ✓ ***Experiments correspond to model***
- ✓ ***Estimated broadening for 2 J***
- ✓ ***Zeonor (COP) included***

E.A. Khazanov *et al*, Post-compression of femtosecond laser pulses using self-phase modulation: from kilowatts to petawatts in 40 years, Quantum Electron. **52** 208 (2022)

Metrology: Simulation results

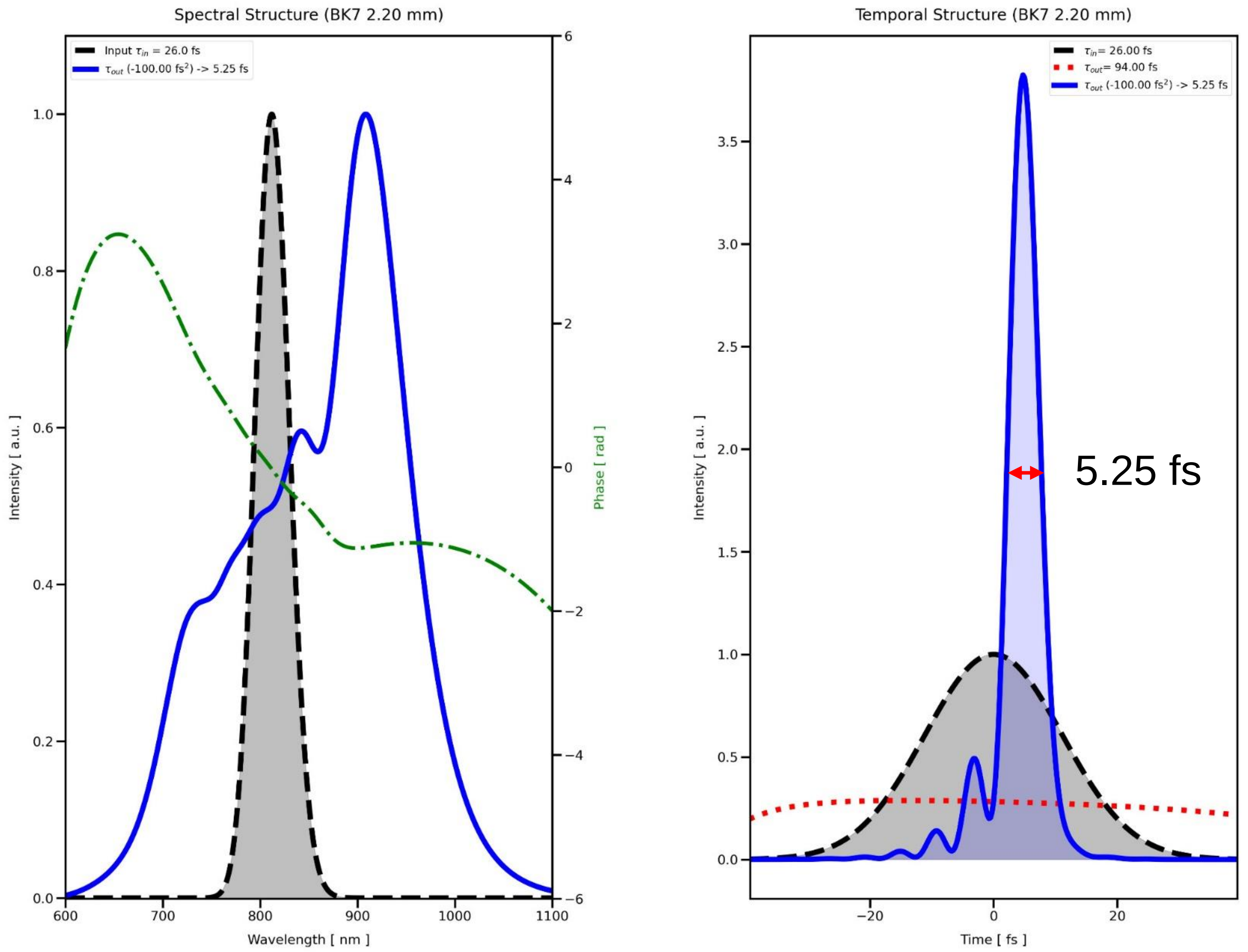


Fig. 10. Simulated spectral broadening and pulse duration for 2 mm BK7 at 2 J, 1 compression stage

Input:
PyNLO library of Python
2 mm BK7, 2 J, 1 compression stage

Output 5.25 fs @ELI-NP
100 TW

Broadening metrology
Estimated broadening for 2 J
Estimated pulse duration

Conclusions

- **ELI-NP; 26 fs-11 fs- 5fs (>5 fold compression 2 J)**
  - ✓ Complete metrology of post-compressed pulses
  - ✓ Stability by mastering GDD and TOD;
  - ✓ TSR and DM factor
  - ✓ Increase in intensity;
  - ✓ Proof of concept for close to single cycle at 2 J

Electrons, Protons, Neutrons, Gamma
Lasers engineering
Medical field
Exawatt concept

Outlook

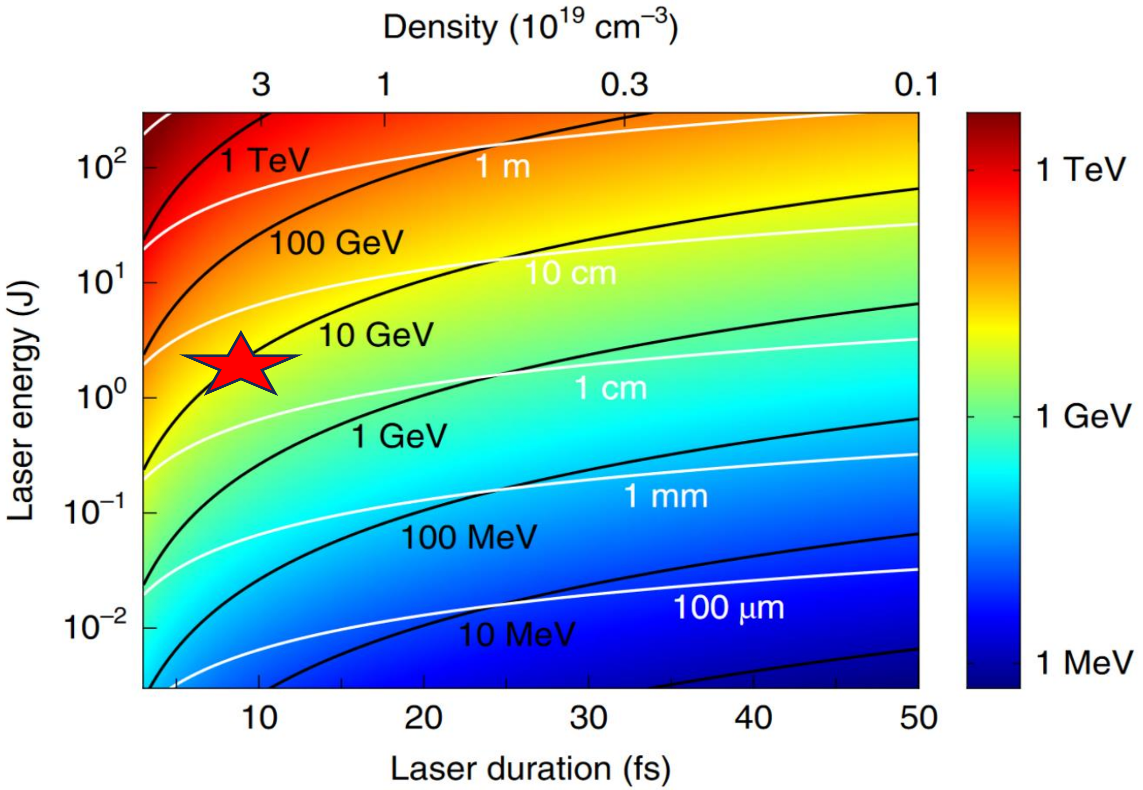


Fig. 11

Evolution of energy gain with accelerator, laser and plasma parameters.

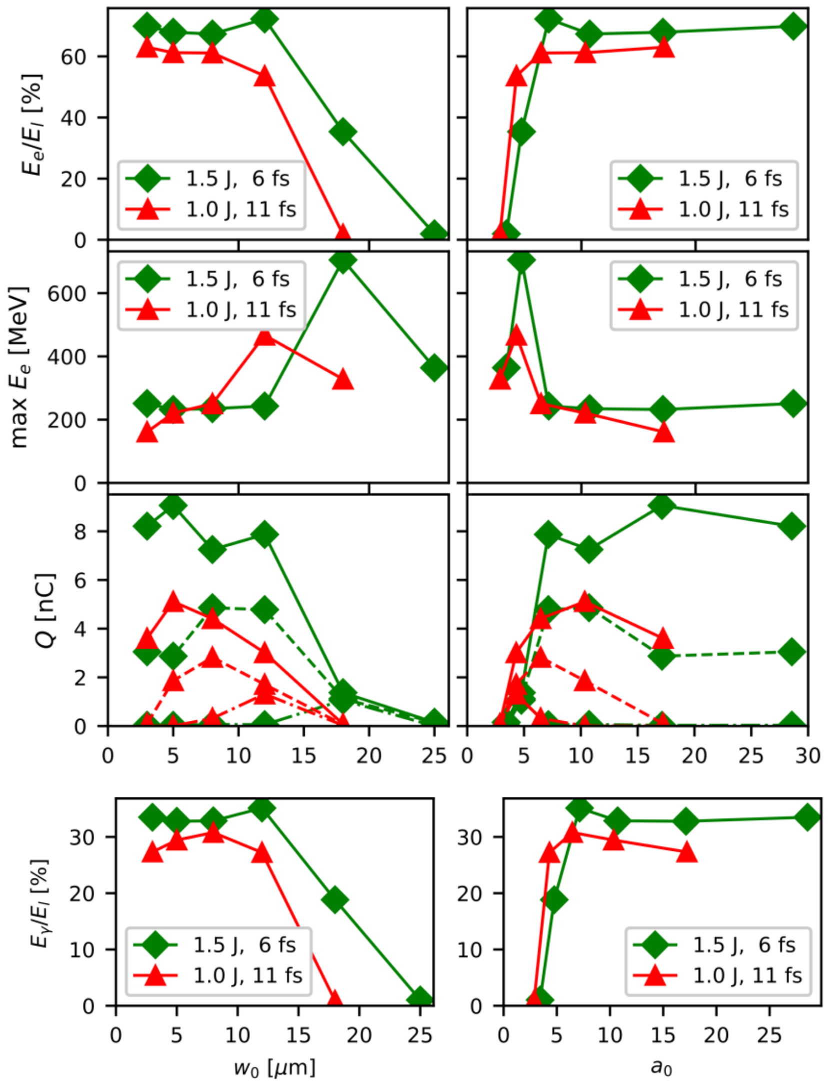


Fig. 12. Secondary sources: electron and gamma, using the results of ELI-NP campaign

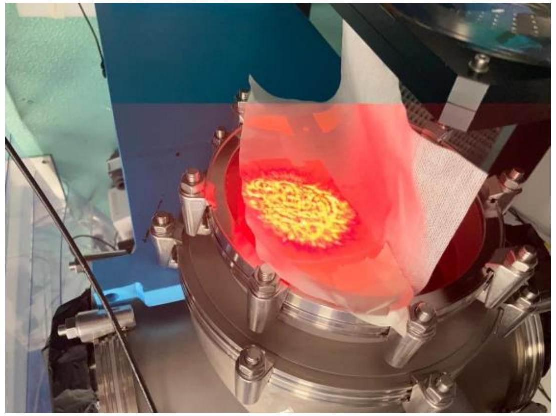
C. Caizergues , S. Smartsev, V. Malka, and C. Thaury, Phase-locked laser-wakefield electron acceleration, Nature Photonics, 2020

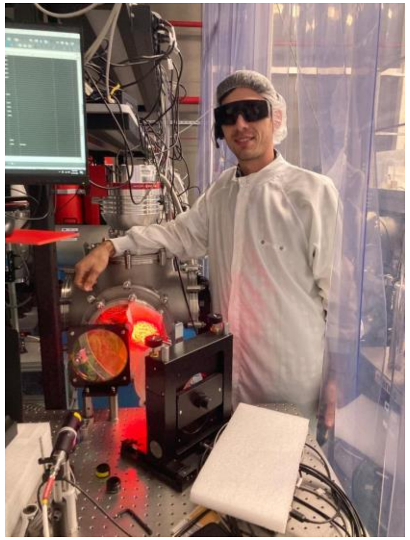
Courtesy of V. Horny and P. Tomassini

Post compression experiment, **19**:30, **Friday**, ELI-NP, 100 TW

Happiness after the first STCs were measured

With the help of a great team!!
D. Ursescu, D. Matei, S. Popa, M. Talposi, V. Iancu, R. Ungureanu, S. Roeder, V. Bagnoud
+ LSD operation team, THALES





LIDT& SPM –100 TW

Thank you for your attention!

Mulțumesc pentru atenție!

Let there be questions!

Thank you! ありがとうございました Danke! Ευχαριστίες Köszönöm Grazie Merci beaucoup! Děkuji благодаря Terima kasih Спасибо