

*Reflecting Petawatt lasers off relativistic plasma mirrors:  
a realistic path to the Schwinger limit*

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### *Boosting ultraintense lasers using curved relativistic mirrors*

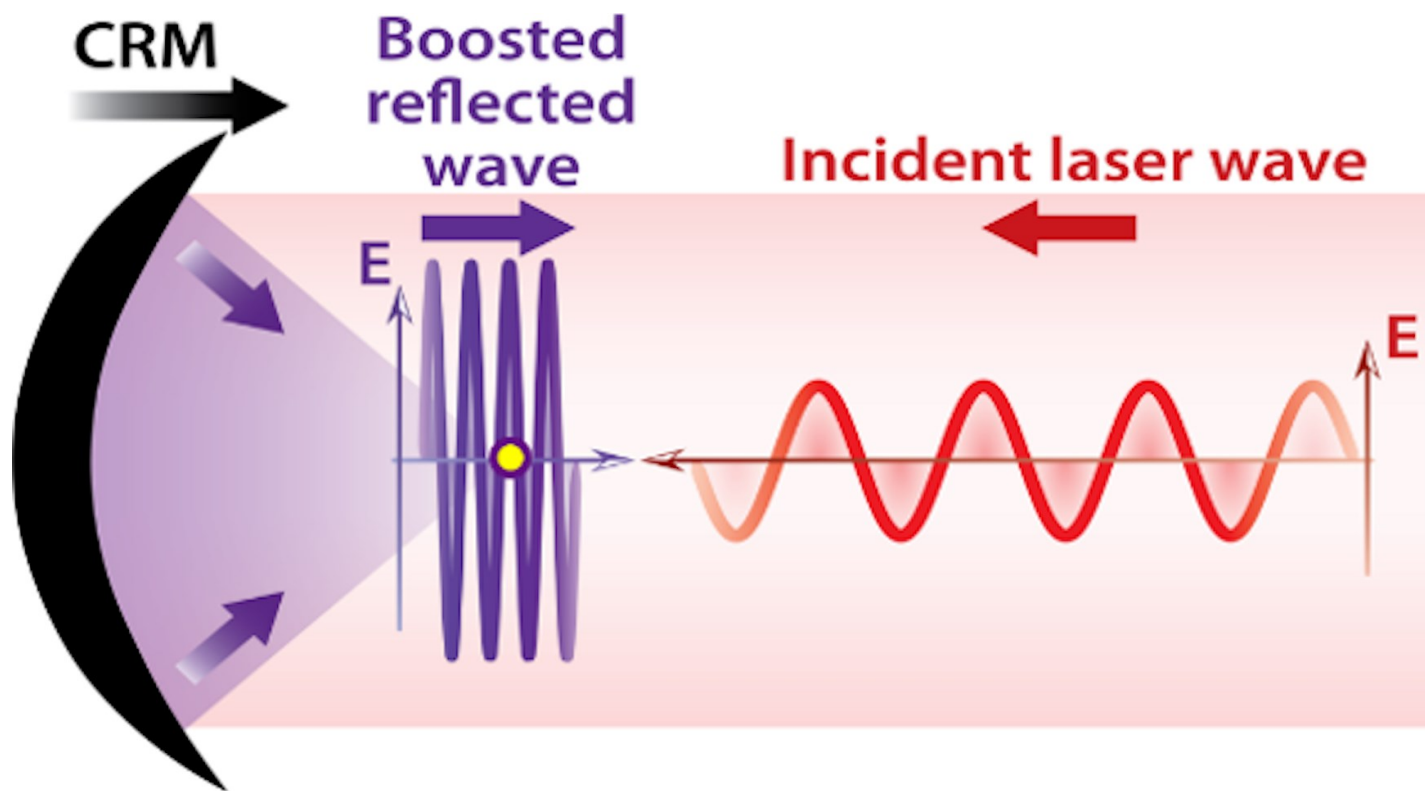
- the efficient wavelength down-conversion of a high-power laser pulse is in principle possible by reflecting this pulse on a mirror moving at a velocity  $v$  close to the speed of light:., a ‘relativistic mirror’ (RM).
- upon reflection on such a mirror, the laser pulse gets down-converted at wavelength  $\lambda$  by a factor  $\alpha \approx 1/4\gamma^2$  (with  $\gamma = (1 - v^2/c^2)^{-1/2}$  the mirror Lorentz factor) and compressed in time by the same factor.
- if  $\gamma \geq 3$ , a femtosecond laser pulse can thus be compressed down to the attosecond time range (1 as =  $10^{-18}$  s). Assuming perfect reflection, the light beam intensity then gets boosted by  $1/\alpha \gg 1$ .
- the focal spot size of a light beamscales linearly with its wavelength  $\lambda \rightarrow$  further gain can therefore be achieved to more strongly concentrate the light energy in space.
- after reflection by an RM, the light can be focused to an area  $\alpha^2$  smaller than the initial laser beam, leading to a gain of  $1/\alpha^2$  on the light intensity.

The combination of these spatial and temporal effects finally results in a total intensity gain that scales as  $1/\alpha^3 \propto \gamma^6$ .

These two compression steps can be combined into a single stage, by reflecting the light beam on a ‘curved relativistic mirror’ (CRM), Fig. 1

Such a CRM simultaneously compresses the pulse in time, down-converts it in wavelength and imprints a wavefront curvature which induces the subsequent focusing of the reflected field.

Reflecting a PW-class laser beam on a CRM with even a moderate Lorentz factor  $\gamma \approx 10$  would thus make the Schwinger limit within experimental reach. The actual implementation of this approach faces considerable experimental problems. How can be obtained such RMs, with suitably large  $\gamma$  factor?



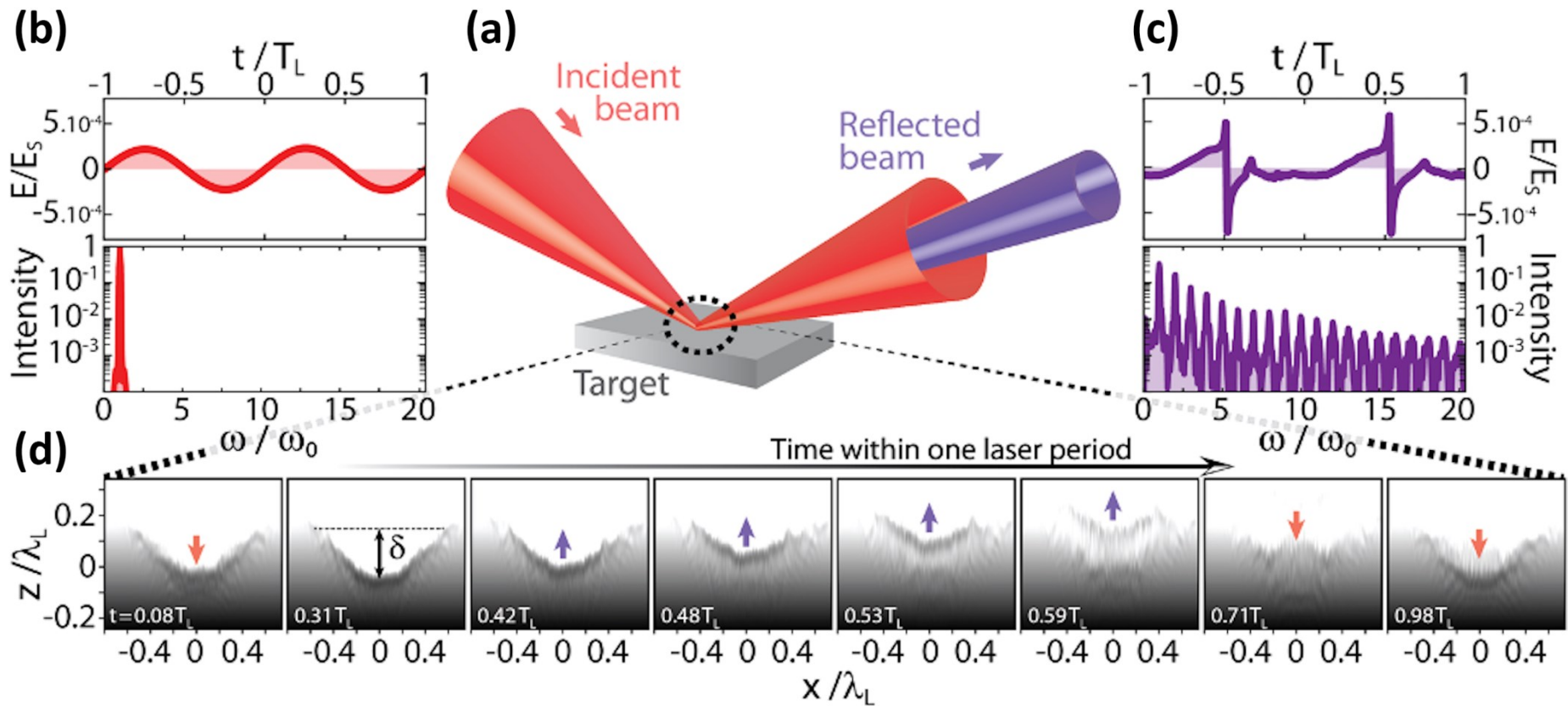
**Fig 1.** Schema de principiu a cresterii (boosting) campului electric  $E$  al unei unde luminoase folosind CRM (curved relativistic mirror). Punctul galben corespunde zonei de focalizare a CRM in vid.

## *Exploiting ultrahigh-intensity laser–plasma interactions to create RMs*

- when exposed to a laser beam with  $I > 10^{18}$  W/cm<sup>2</sup>, electrons are set in relativistic motion. A natural idea is thus to use a first ultraintense laser beam to create an RM by inducing a collective relativistic motion of electrons in a target, and then reflect a second laser beam on this RM
- this can be achieved by focusing such a laser beam on one side of a very thin foil: electrons from the foil are collectively pushed forward by the laser radiation pressure, thus creating an RM at the rear side of the foil. A second counter-propagating laser beam can, in turn, be reflected from this RM, to be boosted in intensity.
- new approach is provided by “**relativistic plasma mirrors**” (**p-RMs**), created when an ultraintense laser pulse hits a solid target. It has considerable advantages, in particular:
  - (i) it relies on a much simpler interaction configuration, where a single ultraintense laser beam both creates the RM and gets reflected by this RM;
  - (ii) a significant number of experiments with 100-TW-class lasers have demonstrated that these mirrors are highly controllable and their physical response to the incident field is very reproducible
  - (iii) it is possible to create curved relativistic plasma mirrors (p-CRMs), such that the reflected beam converges directly to a tight focus. This avoids the considerable effort of collecting and refocusing the short-wavelength, spectrally broad, intense attosecond pulses.

## *Basic physics of plasma mirrors*

- a plasma mirror is a dense plasma created at the surface of a solid target when this target is irradiated and gets ionized by an intense ultrashort laser pulse. Owing to its high electron density (few  $10^{23} \text{ cm}^{-3}$ , i.e.,  $10^2$ – $10^3$  times the critical density  $n_c$  for the laser frequency), it efficiently reflects the incident laser field. In addition, owing to the ultrashort laser pulse duration, plasma expansion into vacuum is very limited during the interaction.
- plasma mirrors specularly reflect the incident beam, and can be viewed as high-quality mirrors suitable for ultraintense ultrashort laser beams
- to induce large intensity boosts on the reflected laser beam, plasma mirrors need to be set in relativistic motion, which is possible when they are exposed to laser intensities ranging from at least  $10^{18} \text{ W/cm}^2$  up to the highest laserintensities available to date, of a few  $10^{22} \text{ W/cm}^2$ . The incident laser field then drives a periodic oscillation of the plasma mirror surface, at relativistic velocities (Figure2).
- this relativistic oscillating mirror (ROM)1 induces a periodic Doppler effect on the reflected field. Each time the mirror surface moves outward, it compresses the laser energy in time, leading to a sharpening of the reflected waveform (Figures 2(b) and 2(c)). Although still periodic in time, this waveform is no longer sinusoidal: its spectrum thus consists of the combination of the laser frequency  $\omega_L$  with a comb of high-order harmonics of frequencies  $n\omega_L$
- This physical process is now fairly well-understood theoretically. While complete analytical model is still missing, it can be described with high fidelity by numerical simulations based on the particle-in-cell (PIC) method.



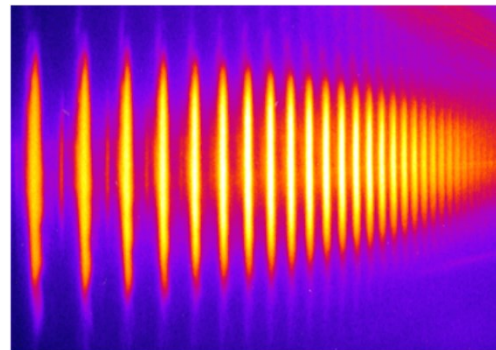
**Fig 1.** (a) Reflexia unui fascicol laser ultraintens pe o oglinda de plasma. La intensitati foarte mari acest laser - reprezentare campul  $E(t)$  a laserului (b) sus, intensitatea (b) jos - va produce oscilatii relativiste ale suprafetei plasmei. Consecinta: asupra fascicolului reflectat se produce efectul Doppler rezultand o unda reflectata distorsionata periodic (c) cu un spectru care consta dintr-o multitudine de armonice de ordin inalt (c) jos. (d) Imagini ale densitatii de electroni la suprafata oglinzii de plasma (intr-un sistem Lorentz in care laserul are incidenta normala pe plasma), la diferite momente din ciclul laserului, observandu-se doua efecte: oscilatiile relativiste ale suprafetei plasmei, curbura spatiala a suprafetei acesteia indusa de presiunea radiatiei a campului laserului incident. Reprezentarea corespunde unei simulari PIC cu o intensitate laser  $I = 10^{22}$  W/cm<sup>2</sup>.

## Experimental knowhow on relativistic plasma mirrors

### First-generation experiments (circa 2005→2012)

- the very first challenge to address in the investigation of relativistic plasma mirrors was obviously to prove that such mirrors could actually be created in experiments. This implied producing a very dense plasma at the surface of a solid target, with a density gradient between this dense plasma and vacuum of only a fraction of the laser wavelength  $\lambda_L$ .
- as such plasmas expand with typical velocities of a few tens of nanometres/picosecond, the initial solid target must be ionized only in the rising edge of the incident laser pulse, less than a few picoseconds before its maximum. Fulfilling this stringent condition turned out to be very challenging when the peak intensity of the laser pulse is very high ( $I > 10^{18}$  W/cm<sup>2</sup>). Indeed, the intensity of the comparatively very weak parasite light that precedes these pulses for several nanoseconds (the so-called temporal pedestal, unavoidable with the CPA laser technology), then gets large enough to ionize the target well before the main pulse, and thus initiates plasma expansion. Plasmas created in such conditions have very long density gradient, such that the optical quality of the laser beam is not preserved upon reflection: they are no longer plasma mirrors
- this issue was solved by using one or several other plasma mirrors (prior to the final target), exposed to lower laser intensities, as ultrafast high-dynamic optical switches to reduce the temporal pedestal by orders of magnitude. Once this issue was solved, high-quality beams comprising tens of harmonic orders could finally be observed in experiments with 100-TW-class lasers, **Fig 3**.

**Figure 3.** Imagine neprelucrata a unui spectru armonic experimental (ordin  $\approx 10$  (stanga) to 40 (dreapta) generat la reflectixia unui UHI 100 TWlaser (CEA Saclay) pe o oglinda de plasma relativista



## *Second-generation experiments (circa 2012→present)*

- a second generation of experiments started about 10 years ago, with the goal of controlling and measuring the properties of plasma mirrors and of the attosecond pulses that they generate.

### Adjusting the prepulse of the laser beam.

- when a prepulse beam is used to control the density gradient scale length  $L$ , the expansion velocity of the created plasma depends on the local prepulse fluence. Spatially shaping the prepulse fluence profile on target thus results in a spatial modulation of the expansion velocity of the plasma, which in turn leads to the development of a spatial structure of the plasma surface out of the initially flat target surface. This provides a great flexibility for shaping the plasma surface prior to the nonlinear interaction with the main laser beam.

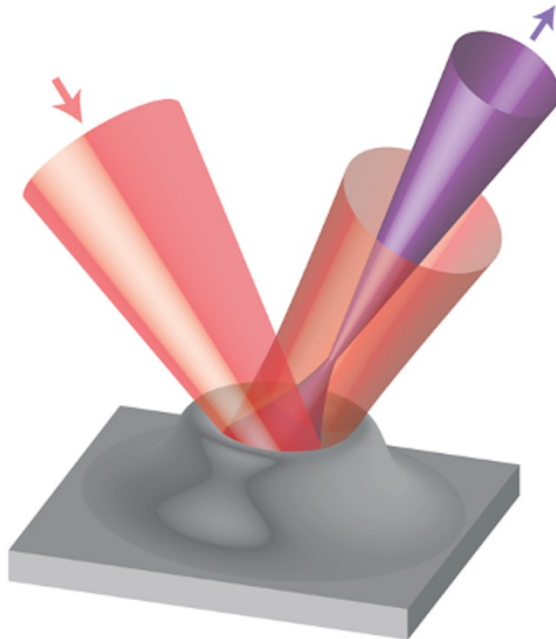


### Tailoring the main ultraintense driving laser field.

- during the interaction of a plasma mirror with an ultraintense laser pulse, the plasma dynamics is dominated by the collective ‘coherent’ motion of a large ensemble of electrons, directly driven by the laser fields  $\mathbf{E}(r,t)$  and  $\mathbf{B}(r,t)$ . This dynamics is thus controllable by tailoring the driving laser field in time, space or space–time. Such a control has been demonstrated in a number of experiments, which have for instance enabled the generation of isolated attosecond pulses from plasma mirrors using laser fields with ultrafast wavefront rotation (attosecond lighthouse effect)

## *Intensity boosting using relativistic plasma mirrors*

- intensity boosting using p-CRM was first studied analytically 17 years ago, assuming plasma mirrors created on ideally curved pre-shaped solid targets. At the time, it was believed that the harmonic spectra generated from plasma mirrors follow a universal power-law decay, as  $n^{-p}$ , where  $5/2 < p < 3$  and  $n$  is the harmonic order.
- since this initial work, multiple theoretical/numerical studies have shown that the harmonic power law decay with  $5/2 < p < 3$  is actually not universal, but rather restricted to specific interaction conditions. These studies also demonstrated that much more favourable shapes of the harmonic spectra can be produced, for instance by optimizing the bulk plasma density at the target surface. Leveraging on these advances, the idea of using p-CRM to boost the intensity of ultraintense lasers has recently been revived and carefully validated theoretically employing the very first 3D PIC simulations of plasma mirror focusing



**Fig 4.** Schema de principiu a cresterii intensitatii folosind p-CRM. Curbura suprafetei de plasma poate fi indusa ori de presiunea radiatiei sau prin metode mai elaborate (tinte solide cu forme prestabilite de tip parabole)

## *Estimation of achievable light intensities*

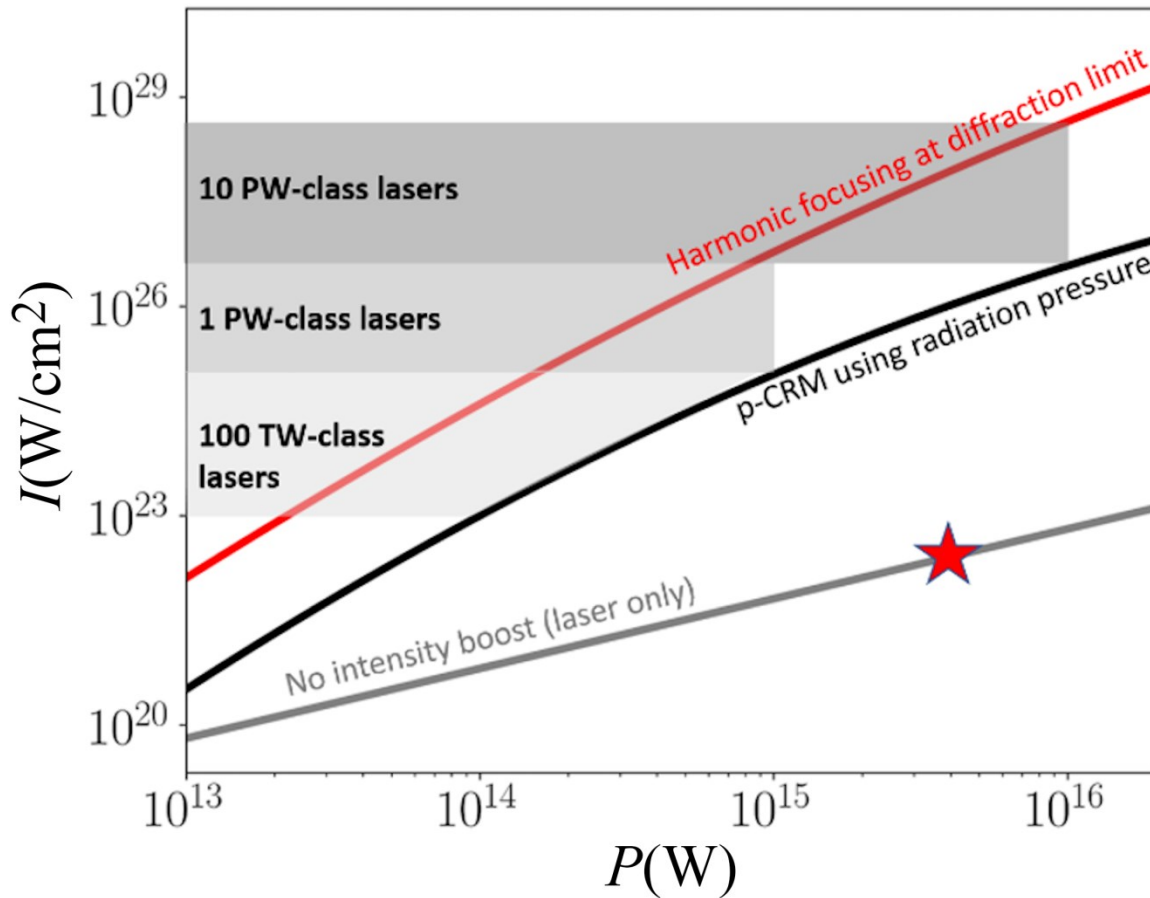
What are the light intensities that we can aim at by applying relativistic plasma mirrors to terawatt (TW) and PW CPA lasers?

This is specified in Figure 5, obtained from the combination of the previous analytical model with numerical simulations. The achieved intensity gain  $I$  (ratio of black or red curve to the grey curve) increases with laser power because the p-CRM can be driven more efficiently with more powerful lasers.

We can use the curvature of plasma mirrors induced by radiation pressure. This curvature ‘comes for free’ in the interaction with plasma mirrors, but is only weakly controllable and cannot be arbitrarily increased to induce a very tight focusing of the harmonics. Using this scheme we can have gains  $I_1 \approx 10^3$ , resulting in intensities of  $10^{23}$  W/cm<sup>2</sup> on 100-TW-class lasers, higher than the present intensity world record and  $\geq 10^{25}$  W/cm<sup>2</sup> with PW-class lasers, already sufficient to induce clearly observable SF QED effects.

The upper curve corresponds to the truly optimal limit of our intensity boosting scheme, where harmonics are focused down to their diffraction limit (spot size  $\approx \lambda_L/n$ ). This requires using p-CRM with a larger curvature, and hence larger depth  $\delta$  (typically  $\delta \approx \lambda_L = 800$  nm). The experimental challenge is to create relativistic plasma mirrors with such curvatures, while avoiding spatial aberrations. If successfully implemented on the most powerful lasers available nowadays, this would lead to intensity gains of  $I_2 \approx 10^6$ , resulting in intensities of a few  $10^{28}$  W/cm<sup>2</sup>, approaching the Schwinger limit.

The intensity value that can actually be reached experimentally between these two extremes will essentially depend on how tightly one manages to focus the beam reflected by the p-CRM (depending, e.g., on spatial aberrations of the p-CRM), and on the peak power of the most powerful laser on which this scheme can be implemented.



**Fig. 5.** Intensitatea luminoasa ca functie de puterea  $P$  din peakul laser  
 Curba gri: intensitatea maxima care se poate obtine din laserul propriu zis  
 Curba neagra: cu intensitatea marita, curbura p-CRM fiind indusa de presiunea radiatiei  
 Curba rosie : o curbura optimizata care permite focalizarea armonicelor la limita lor de difractie. Steluta rosie indica recordul de intensitate obtinut cu laser de 4 PW [J. W. Yoon, C. Jeon, J. Shin, S. K. Lee, H. W. Lee, I. W. Choi, H. T. Kim, J. H. Sung, and C. H. Nam, *Opt. Express* 27, 20412 (2019)]  
 Zonele gri indica intervalele estimate pentru intensitatea luminoasa care s-ar putea obtine in functie de clasa de putere a laserului folosit pentru iradierea unei oglinzi de plasma relativista

## *Conclusions*

- the goal to increase further and further laser the intensity can be achieved by reflecting these laser beams off a mirror in relativistic motion, to induce a Doppler effect that compresses the light pulse in time down to the attosecond range and converts it to shorter wavelengths, which can then be focused much more tightly than the initial laser light.
- this means a major experimental challenge: how to generate such relativistic mirrors? This challenge could nowadays be tackled by using so-called ‘relativistic plasma mirrors’. Approaching the Schwinger limit in the coming years by applying this scheme to the latest generation of petawatt-class lasers can be a challenging but realistic objective.

## *References*

*High Power Laser Science and Engineering*, (2021), Vol. 9, e6, 13 pages.  
doi:[10.1017/hpl.2020.46](https://doi.org/10.1017/hpl.2020.46)

*Multumesc !*