Workshop on Beam Acceleration in Crystals and Nanostructures, 24-25 June 2019, Fermilab

Relativistic Flying Mirrors for intense short pulse X-ray generation

Stepan Bulanov

BELLA Center, ATAP Division, LBNL

Supported by the Office of Science of the US DOE under Contract No. DE-AC02-05CH11231.

BERKELEY LAB U.S. DEPARTMENT OF ENERGY Office of Science BELLA ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

In collaboration with

Lawrence Berkeley National Laboratory, USA

E. Esarey
C. B. Schroeder
W. P. Leemans

Kansai Photon Science Institute, QST, Japan

T. Zh. Esirkepov
M. Kando
J. K. Koga

ELI Beamlines, Czech Republic

G. Korn
S. V. Bulanov

Osaka University, Japan

A. G. Zhidkov

University of Michigan, USA

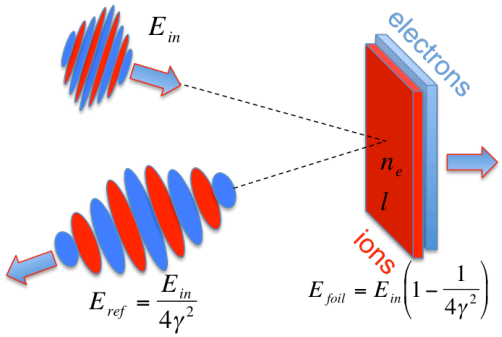
A. Maksimchuk

University of Pisa, Italy

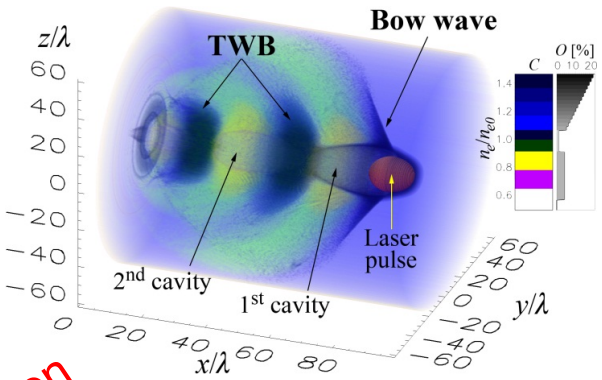
F. Pegoraro

High Intensity Laser Facilities will allow studies of different regimes of laser-matter interaction

Ion Acceleration

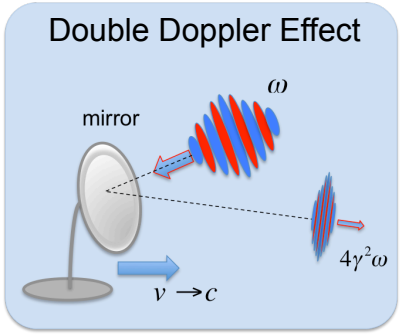


Electron Acceleration



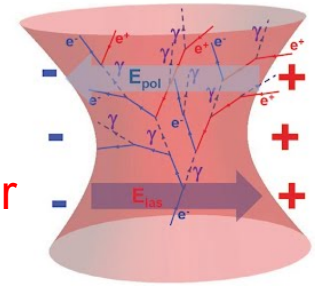
RFM generation

Relativistic Flying Mirrors



RFM generation

High Intensity Particle Physics



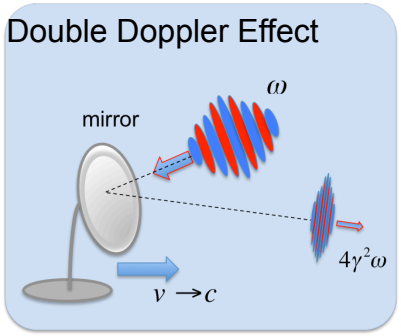
RFM can be used for

Relativistic Flying Mirrors generate high frequency high intensity electromagnetic pulses

Ion Acceleration

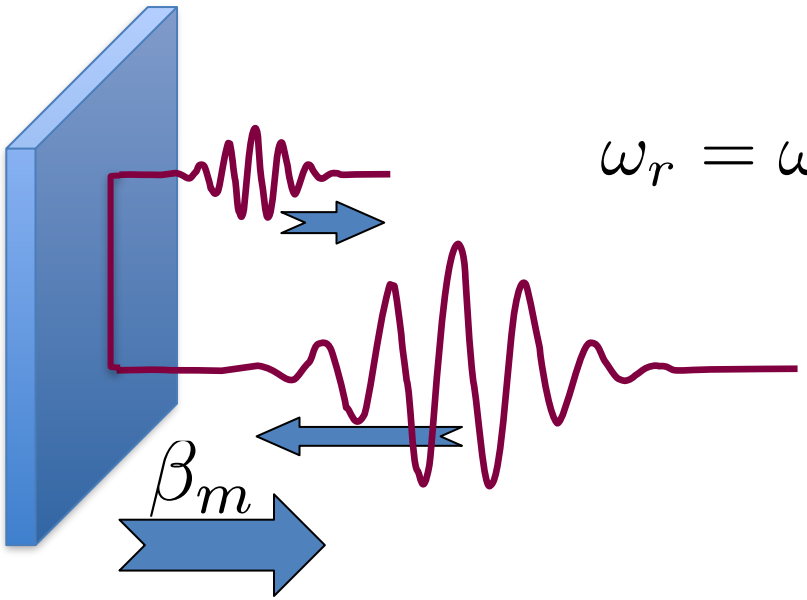
Electron Acceleration

Relativistic Flying Mirrors



High Intensity Particle Physics

Relativistic Flying Mirror scheme is based on the double Doppler effect and provide an effective way of upshifting EM wave frequency and intensity.



$$\omega_r = \omega_0 \frac{1 + 2\beta_m \cos\theta + \beta_m^2}{1 - \beta_m^2}$$

$$\sin\theta_r = \frac{\left(1 - \beta_m^2\right)\sin\theta_0}{1 + 2\beta_m \cos\theta + \beta_m^2}$$

<u>Normal incidence:</u> $$\omega_r = \omega_0 \frac{1 + \beta_m}{1 - \beta_m} = \omega_0 \left(1 + \beta_m\right)^2 \gamma_m^2$$

Relativistic Flying Mirror can be formed by density modulations in plasma (wakes, moving electron layers, solid density foils)

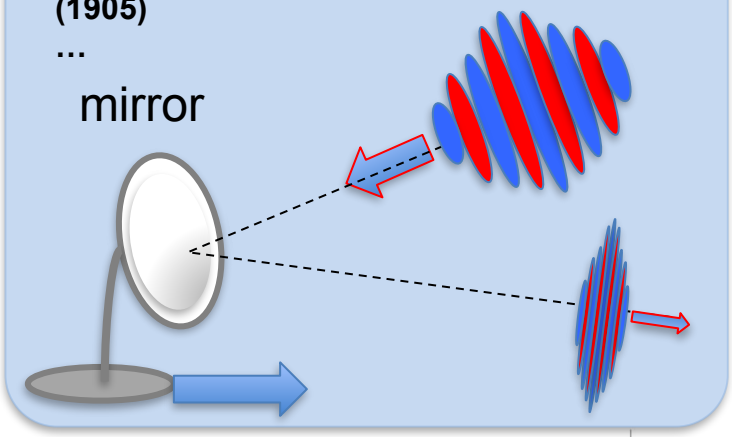
Einstein (1905)

Electromagnetic Pulse Intensification and Shortening by Flying Mirror formed in laser-plasma interaction

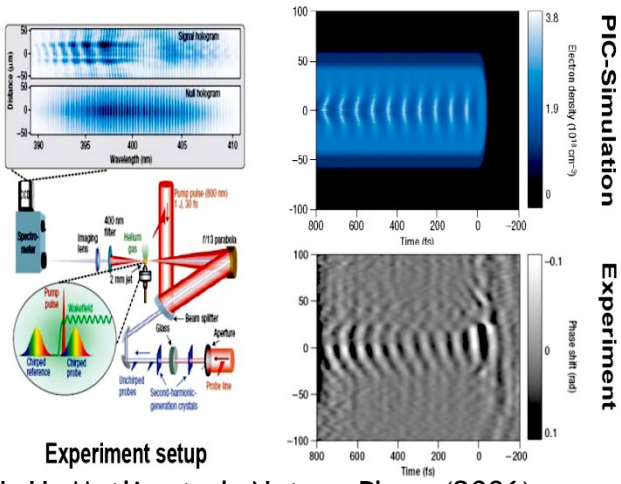
Double Doppler Effect

A. Einstein, Ann. Phys. (Leipzig) 17, 891 (1905)

...



Snapshots of Laser Wake Waves

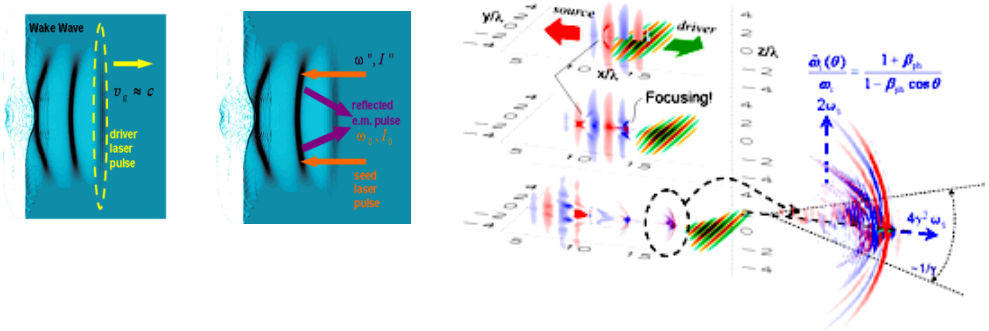


N. H. Matlis et al, Nature Phys. (2006)

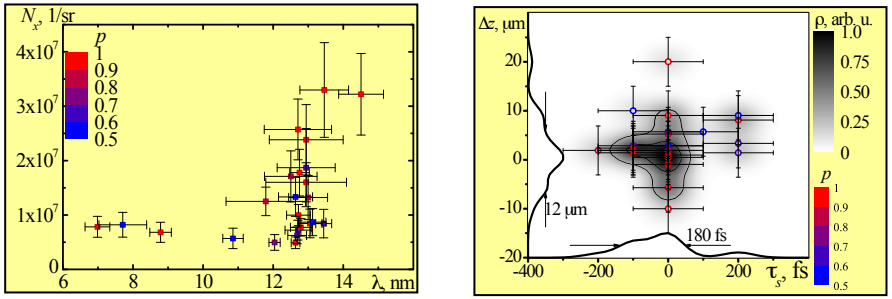
Paraboloidal relativistic mirrors are formed by the wake wave left behind the laser driver pulse

S.V.Bulanov, T. Esirkepov, T. Tajima, Phys.Rev.Lett. 91, 085001 (2003)

Theory



Experiment



λ_x = 14.3 nm

$\Delta\lambda_x$ = 0.3 nm, $\Delta\lambda_x/\lambda_x$ = 0.02

Reflected pulse duration:

τ_x ~ 1.4 fs

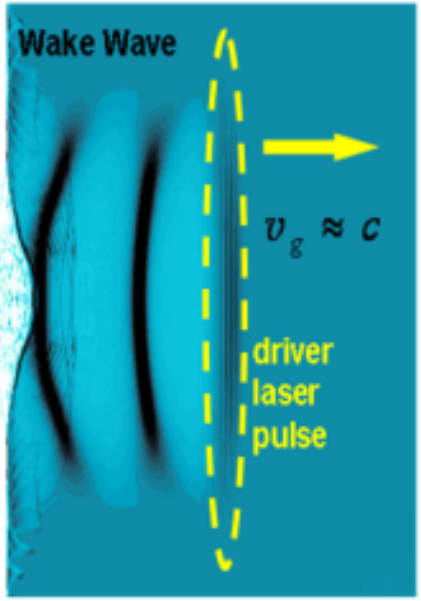
(femtosecond pulse)

M. Kando, et al., Phys. Rev. Lett. 99, 135001 (2007)

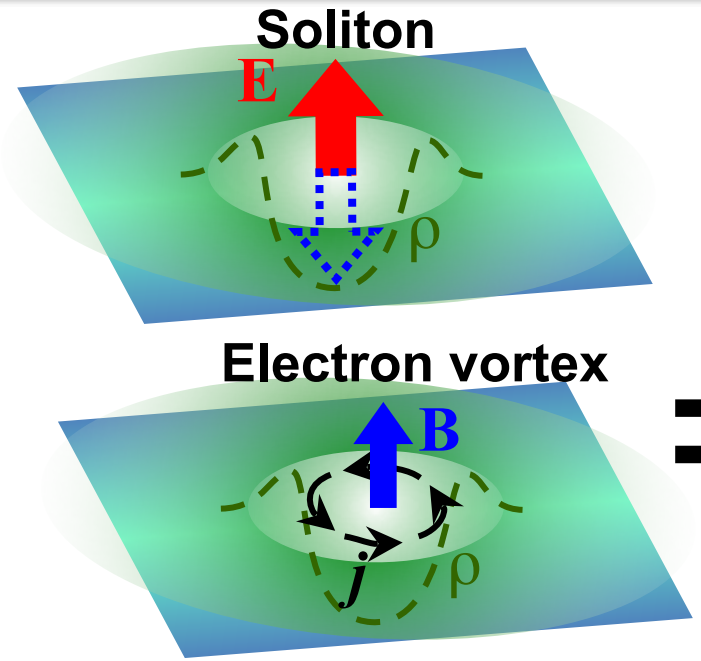
A. S. Pirozhkov, et al., Phys. Plasmas 14, 080904 (2007)

M. Kando, et al., Phys. Rev. Lett., 103, 235003 (2009)

High-intensity electromagnetic pulses can be generated in the interaction of a plasma wakefield with regular nonlinear structures

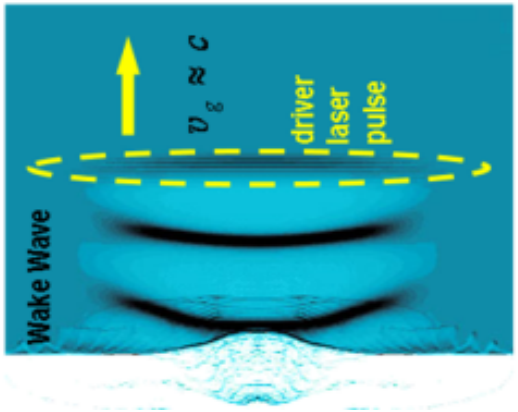


+



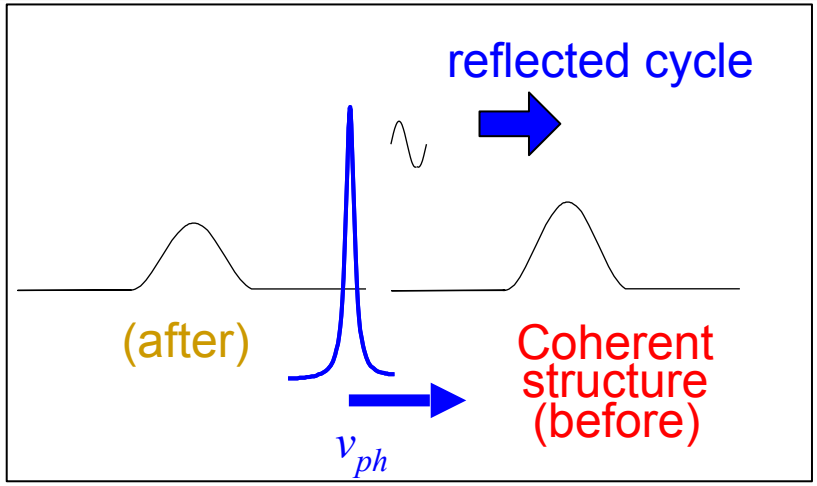
=

Short
high frequency
high intensity
EM pulse



S. S. Bulanov et al PRE (2006)

Scheme of 1D analysis



Coherent structure: field F

Fourier transform $F(\xi) \rightarrow \Phi(k)$

$$F(\xi) = \int \Phi(k)\, e^{ik\xi}\, dk$$

Lorentz transformation to Moving reference frame

$$\Phi(k)\, e^{ik\xi} \rightarrow \Phi(k')e^{ik'\xi'}$$

Reflection: $\tilde{\Phi}(k')e^{ik'\xi'} \rightarrow \rho(k')\, \tilde{\Phi}(k')e^{ik'\xi'}$

Lorentz transformation to Laboratory reference frame

Inverse Fourier transform

Reflected cycle: $F_{ref}(\xi) = \int \rho(k)\, \tilde{\Phi}(k)\, e^{ik\xi}\, dk$

Results of 1D analysis

Soliton

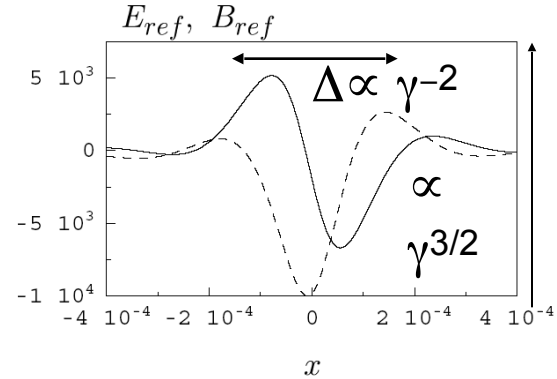
Model field: $A(x,t) = \dfrac{2\varepsilon(\Omega_S)\cosh[\varepsilon(\Omega_S)\omega_{pe}x/c]e^{i\Omega_S t}}{\cosh^2[\varepsilon(\Omega_S)\omega_{pe}x/c] - \varepsilon^2(\Omega_S)} \equiv \mathcal{C}(x)\ e^{i\omega_0 t},$

$\varepsilon(\Omega_S) = (1-\Omega_S^2/\omega_{pe}^2)^{1/2}, \quad \Omega_S < \omega_{pe}$

Reflected cycle:

$$A_{ref}(x,t) = -q\ e^{-q(1+\beta_{ph})\gamma_{ph}(t-x/c)} \int_{-\infty}^{(1+\beta_{ph})\gamma_{ph}(t-x/c)} \mathcal{C}(\gamma_{ph}v_{ph}\tau)\ e^{(q+i\omega_0\gamma_{ph})\tau}\, d\tau$$

$$q = 2\omega_{pe}(2\gamma_{ph})^{1/2}$$



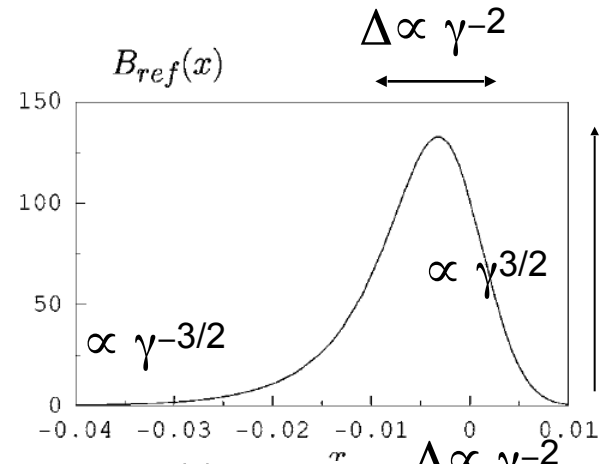
Vortex

Model field: $B = B_0 \exp(-x^2/d_e^2)$

Reflected cycle:

$$\frac{E_{ref}}{\gamma_{ph}^{3/2}B_0} = (8\pi)^{1/2}\exp(\varphi^2 - \psi)\left[1 - \mathrm{erf}\left(\varphi - \frac{\psi}{2\varphi}\right)\right],$$

$$\varphi = 2^{1/2}/\beta_{ph}\gamma_{ph}^{1/2}, \quad \psi = 4\sqrt{2}\gamma_{ph}^{3/2}\omega_{pe}(t - x/c)$$

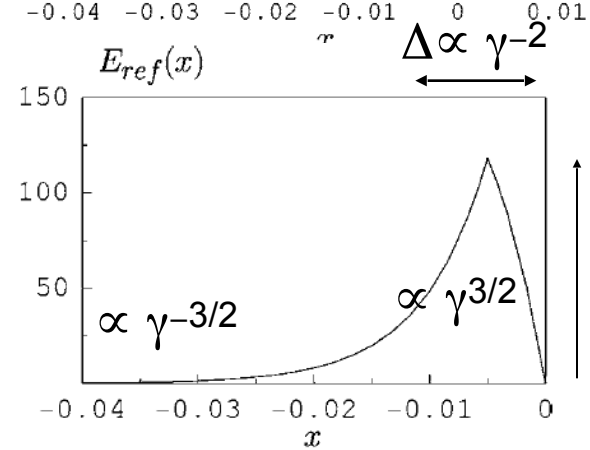


Wake

Model field: $E_w = E_0\theta(x)\,\theta(c/\omega_{pe} - x)$

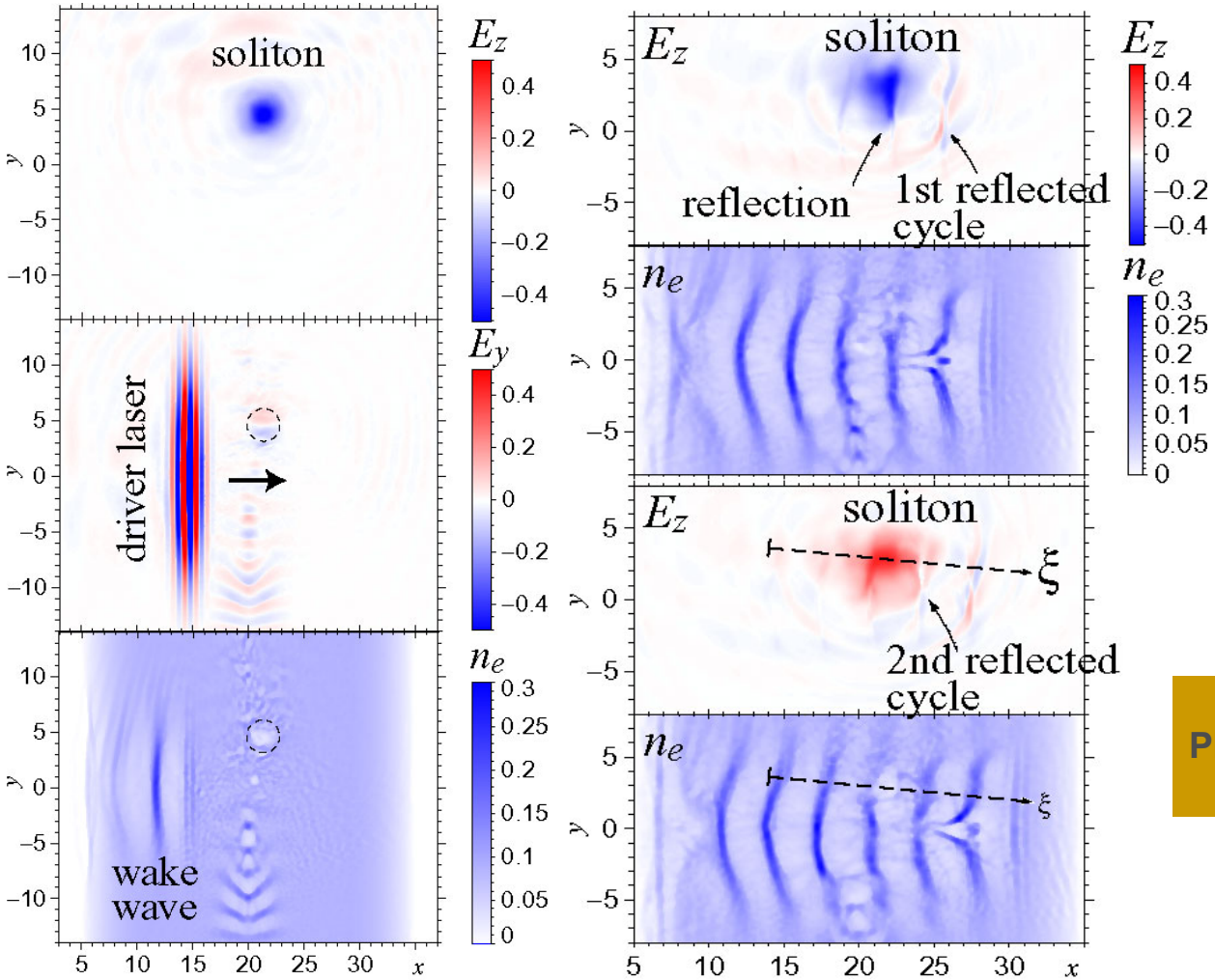
Reflected cycle:

$$E_{ref} = 2\gamma_{ph}^2 E_0\theta(t - x/c)\left[1 - \exp(-\psi) - \left[1 - \exp\left(\frac{2\sqrt{2}}{\sqrt{\gamma_{ph}}} - \psi\right)\right]\theta\left((t - x/c) - \frac{1}{2\omega_{pe}\gamma_{ph}^2}\right)\right]$$



A. Isanin, Phys.Lett.A 337, 107 (2005)

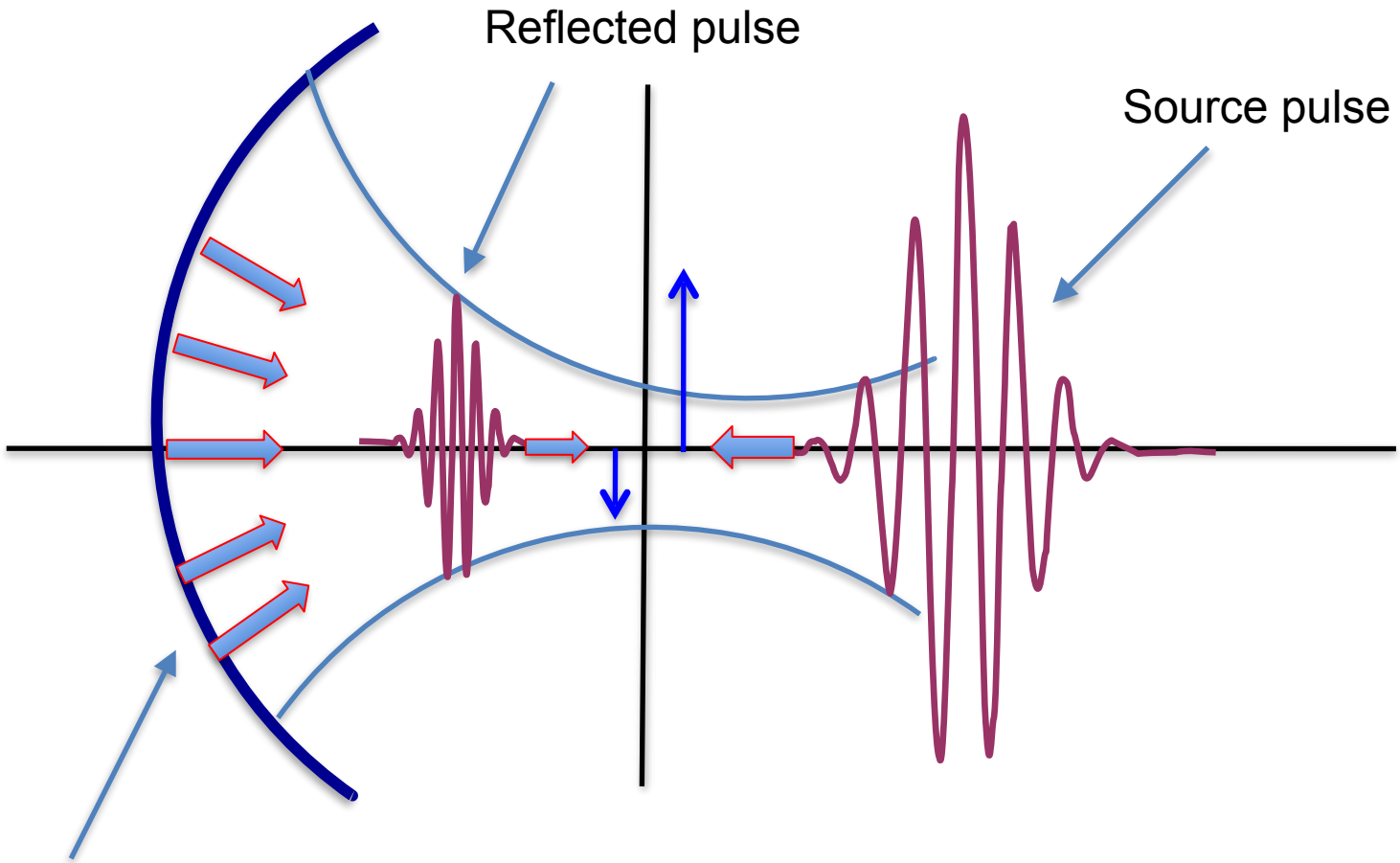
Relativistic Mirrors: generation of ultra-short pulses



S.S.Bulanov et al., Physical Review E 73, 036408 (2006).

How the reflected pulse can be intensified further?

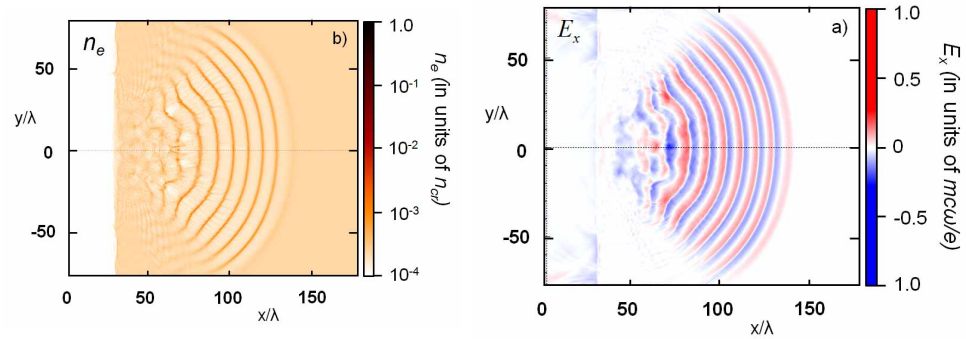
S. S. Bulanov, et al., PoP 2012.



Can it be generated by a focused laser pulse?

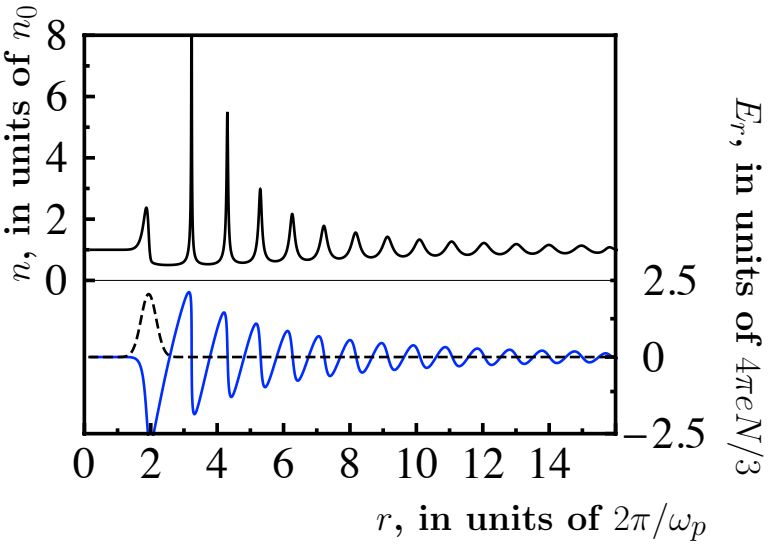
Spherical wave in plasma in the presence of the laser driver

$$\partial_t n + r^{-2}\partial_r(r^2 n v) = 0,$$
$$\partial_t p + v\partial_r p = -E,$$
$$v = p(1+p^2)^{-1/2},$$
$$r^{-2}\partial_r(r^2 E) = 1 - n,$$

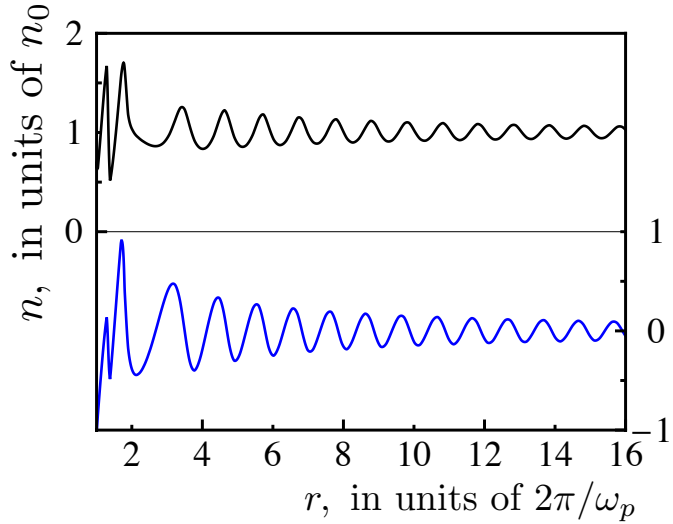


$$f_p = -\partial_r \gamma, \quad \gamma = (1 + a^2 + p^2)^{1/2}$$

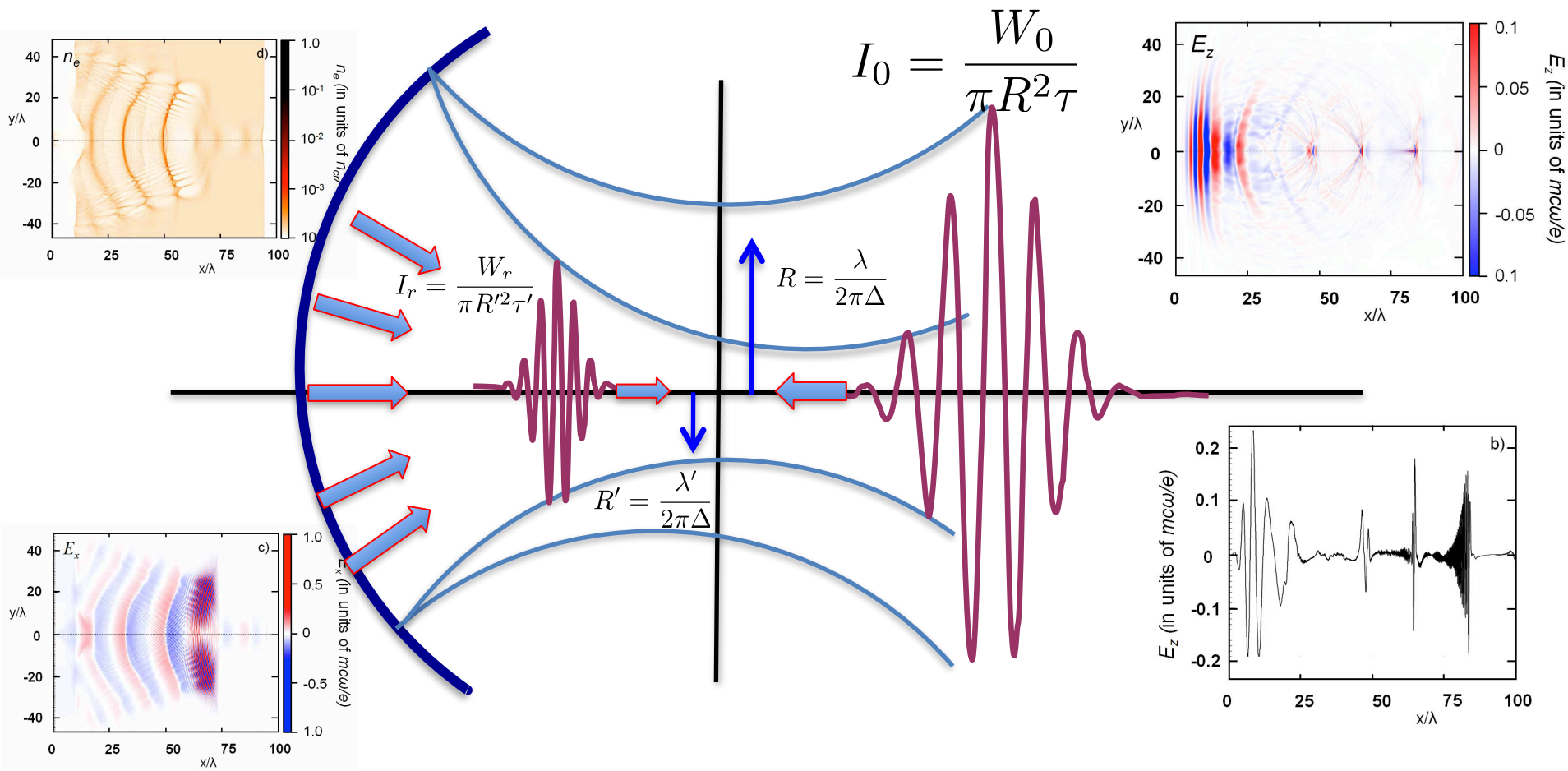
Converging plasma wave



Diverging plasma wave



Spherical Plasma Wave Acting as a Spherical Flying Mirror Focuses the Intensified Pulse

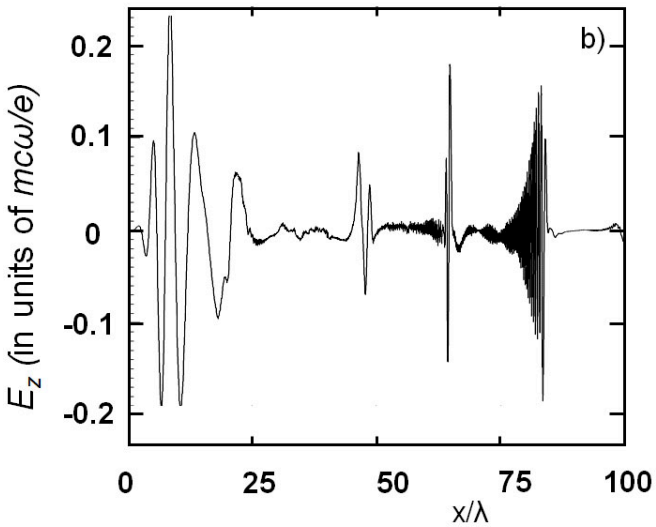


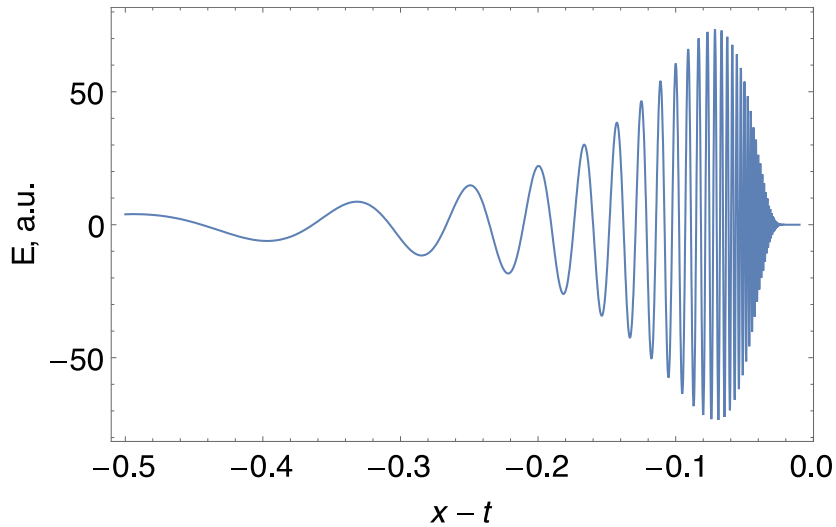
For δ-shaped density cusp the reflection coefficient $\sim \gamma^{-3}$

For $(z-z_{br})^{-2/3}$ density cusp the reflection coefficient $\sim \gamma^{-4}$

$$I_r = 128\gamma^5 I_0$$
$$128\gamma^4 I_0$$

Mirror moving with constant acceleration generates chirped EM pulses





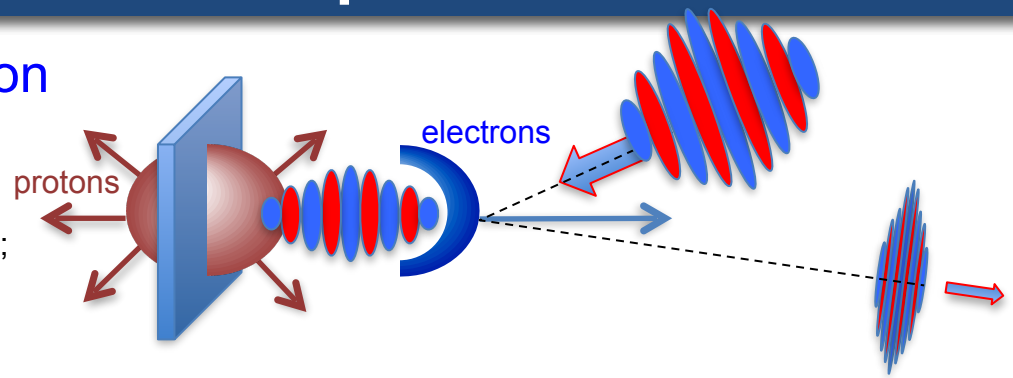
$$E_r = E_0 \frac{\cos\left[k/w^2(x-t)\right]}{w^2(x-t)^2}$$

J. R. Van Meter, S. Carlip, F. V. Hartemann, Am. J. Phys. 69 **(7)**, 2001
S. V. Bulanov, et. al., Physics - Uspekhi 56 (5) 429 (2013)

Flying Mirrors are Generated using the Laser Driven Ion Acceleration Setup

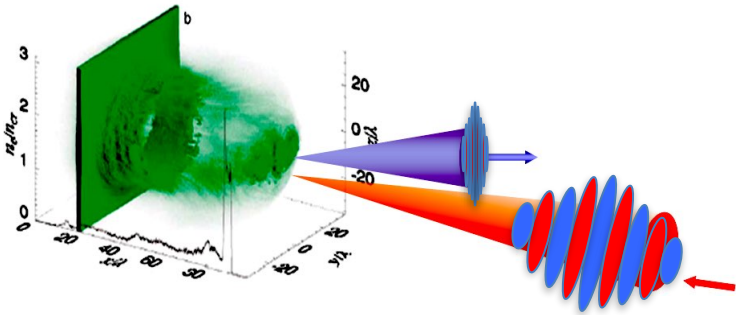
Flying Mirror from Coulomb Explosion

V.V. Kulagin, et al., Phys. Rev. Lett. **99,** 124801 (2007);
D. Habs, et al., Appl. Phys. B **93**, 349 (2008);
J. Meyer-ter-Vehn, H.-C. Wu, Eur. Phys. J. D **55,** 433 (2009);
H.-C. Wu, et al., Phys. Rev. Lett. 104, 234801 (2010).



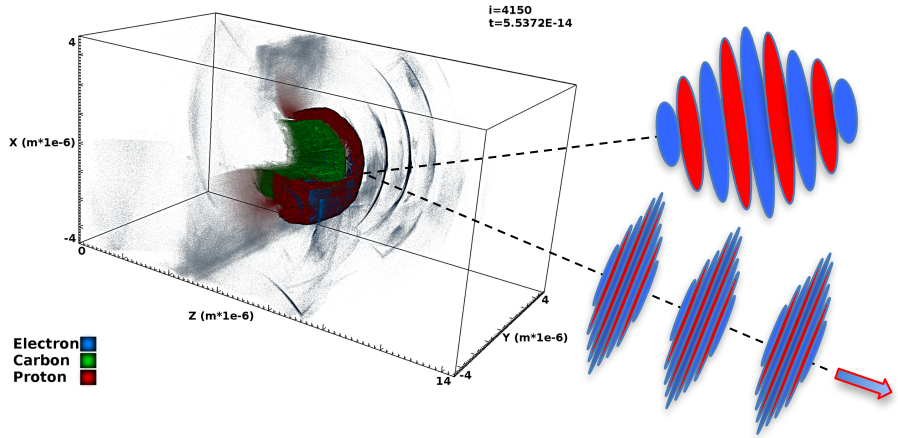
Flying Mirror from Radiation Pressure Acceleration

T.Zh. Esirkepov, et al., Phys. Rev. Lett. 103 (2009) 025002.



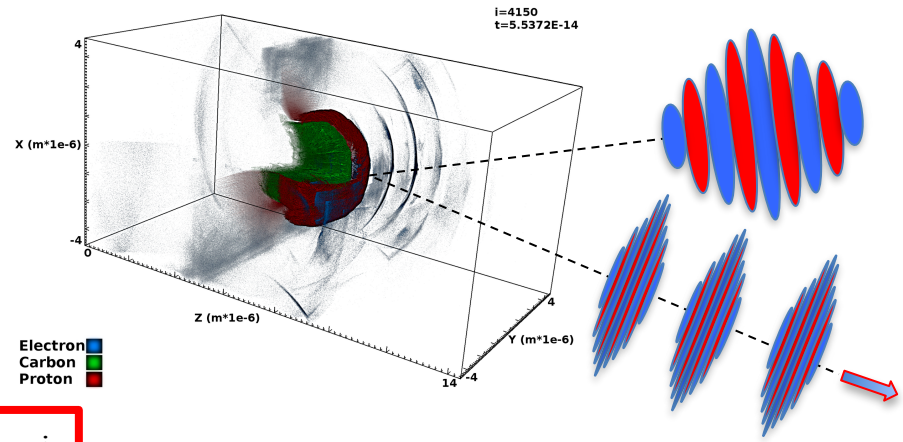
Flying Mirror from multiple electron layers (Directed Coulomb Explosion)

S. S. Bulanov, et al., Phys. Lett. A **374**, 476 (2010).



Reflection from flying relativistic mirror

S. S. Bulanov, et al., Phys. Lett. A **374**, 476 (2010).



Reflected intensity

$$I_r = \frac{16\varepsilon_0^{j\,2}\gamma^4}{4\gamma^2 + \varepsilon_0^{j\,2}} I_0 = \begin{cases} 16\gamma^4 I_0, & \gamma << \varepsilon_0^j \\ 4\varepsilon_0^{j\,2}\gamma^2 I_0, & \gamma >> \varepsilon_0^j \end{cases}$$

Reflected energy

$$E_r = \frac{4\varepsilon_0^{j\,2}\gamma^2}{4\gamma^2 + \varepsilon_0^{j\,2}} E_0 = \begin{cases} 4\gamma^2 E_0, & \gamma << \varepsilon_0^j \\ 4\varepsilon_0^{j\,2} E_0, & \gamma >> \varepsilon_0^j \end{cases}$$

Conclusions

- High Intensity Laser Facilities will allow studies of different regimes of laser-matter interaction
- Relativistic Flying Mirrors generate high frequency high intensity electromagnetic pulses
- Relativistic plasma mirrors can be generated by different plasma structures: wakefields, electron layers, etc.

Thank you!