Efficient acceleration of ion beams and macroparticles for FI in the LICPA accelerator

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1. LICPA – what is this ?
2. Acceleration of ions in the LICPA accelerator
3. Acceleration of a heavy macroparticle in the LICPA accelerator
4. Summary and conclusions

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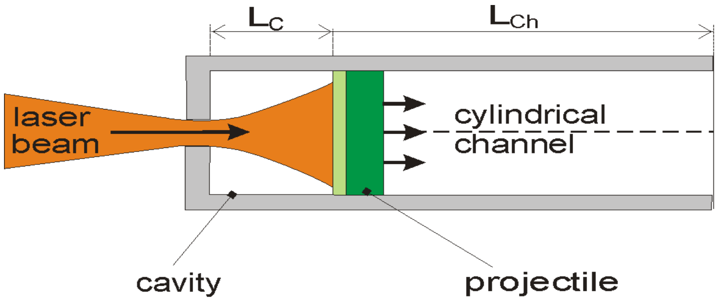
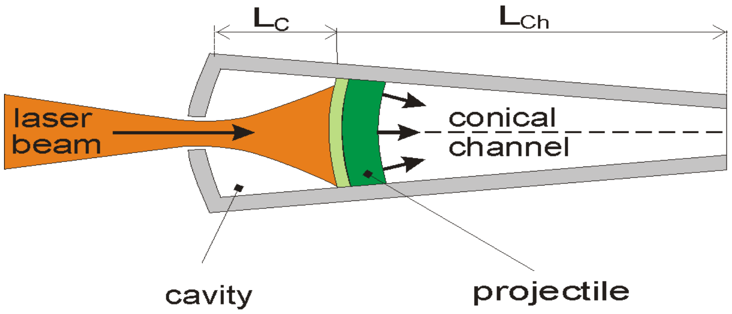
Laser- Induced Cavity Pressure Acceleration (LICPA)

In the LICPA scheme, a projectile placed in a cavity is irradiated by a laser beam introduced into the cavity through a hole and accelerated along a guiding channel by the thermal pressure created in the cavity by the laser-produced plasma or by the photon pressure of the ultraintense laser radiation trapped in the cavity.

The cylindrical accelerator



The conical accelerator



The LICPA accelerator can (potentially) be driven by lasers covering a very broad range of laser energies (from 1J to 1MJ), intensities (from 10^{10} W/cm^2 to 10^{23} W/cm^2 or higher) and pulse lengths (from ns to subps) as well as laser wavelengths (from UV to IR) and repetition rates (up to multi – Hz); as a result, the accelerator can produce dense, fast and ultrafast projectiles of a wide variety of parameters.

Badziak et al., App. Phys. Lett. ***96****, 251502 (2010), Phys. Plasmas* ***19****, 053105 (2012)*

The LICPA Accelerator

Regimes of operation

- **The hydrodynamic regime**

$$\tau_L \leq L_c / \upsilon_{pl} \sim 0.01\ ns \div 10\ ns, \qquad I_L \sim 10^{10} \div 10^{17}\ W/cm^2$$

A projectile is driven by the hydrodynamic (thermal) pressure of hot plasma produced and confined in the accelerator’s cavity

$\mathbf{v_p < 5 \times 10^8\ cm/s}$ (v_p limited by R – T instabilities)

- **The photon pressure regime**

$$\tau_L \leq 10ps, \qquad I_L > 10^{20}\ W/cm^2$$

Acceleration of the projectile is predominantly due to the photon pressure of laser radiation trapped in the cavity

$\mathbf{v_p > 10^9\ cm/s}$ (up to relativistic velocities)

- **The „mixed” regime**

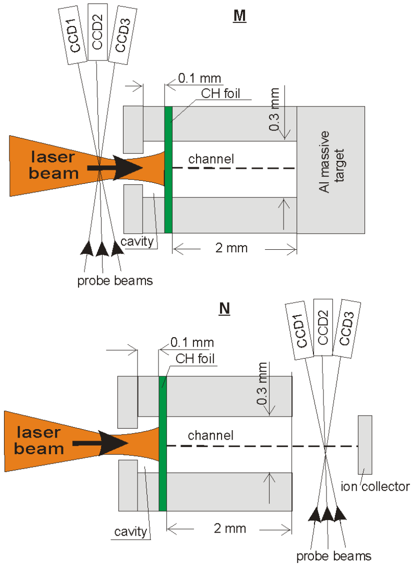
$$\tau_L \sim 0.01\ ps \div 100\ ps, \qquad I_L \sim 10^{17} \div 10^{20}\ W/cm^2$$

Both the photon pressure and the hydrodynamic pressure of very hot plasma (with thermal and hot electrons) can contribute to the acceleration process

$\mathbf{v_p \sim 10^8 \div 10^{10}\ cm/s}$

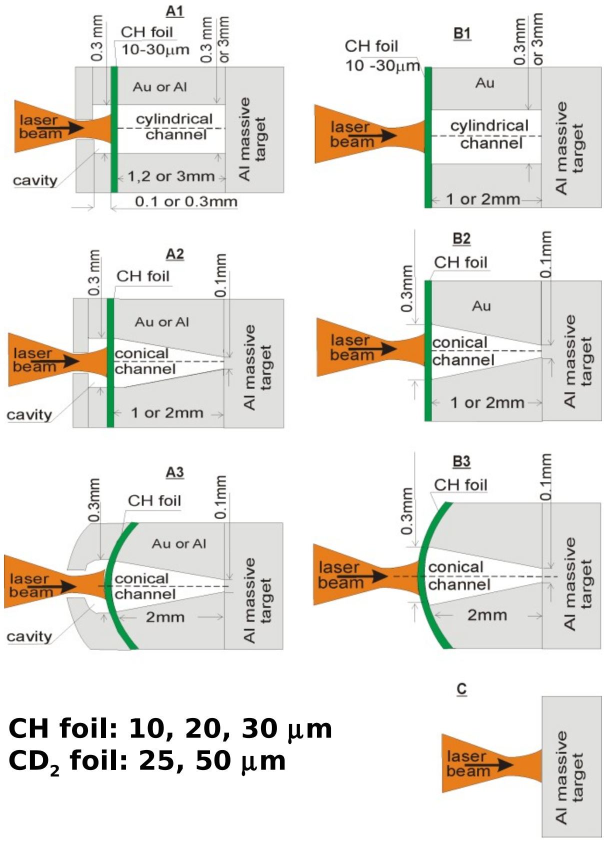
LICPA Experiment at PALS

Scheme



Targets

LICPA **AA**



CH foil: 10, 20, 30 µm
CD_2 foil: 25, 50 µm

Laser:

E_L=50 – 500J, τ_L = 0.3 ns

I_L = 10^{14} – 10^{16} W/cm^2

1ω and 3ω beam

Diagnostics:

- crater measurements
- interferometry
- scintillators (neutron and hard X-rays)
- ion diagnostic (collectors, Thomson parabola)
- X-ray streak camera

LICPA Experiment at PALS

(a) Replicas of craters produced in the massive Al targets by plasma projectiles accelerated in the LICPA and AA schemes with cylindrical and conical geometry.

(b) Results of numerical simulations of craters produced in the Al targets by plasma projectiles

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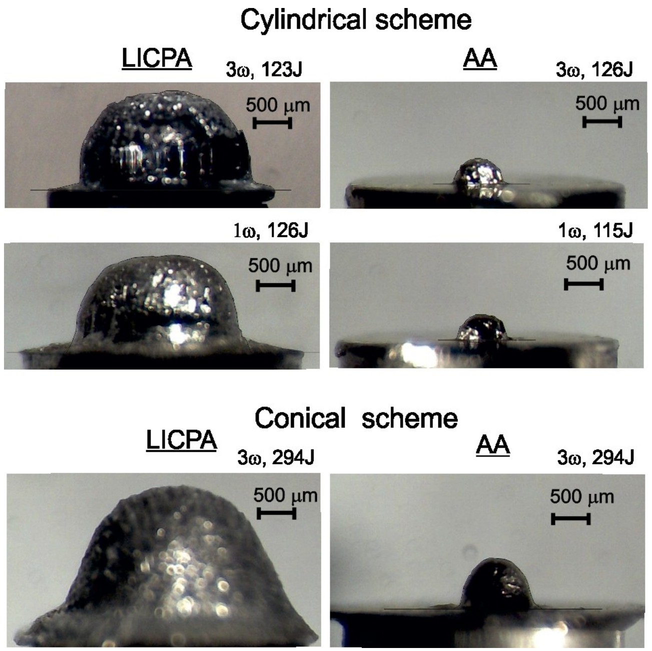
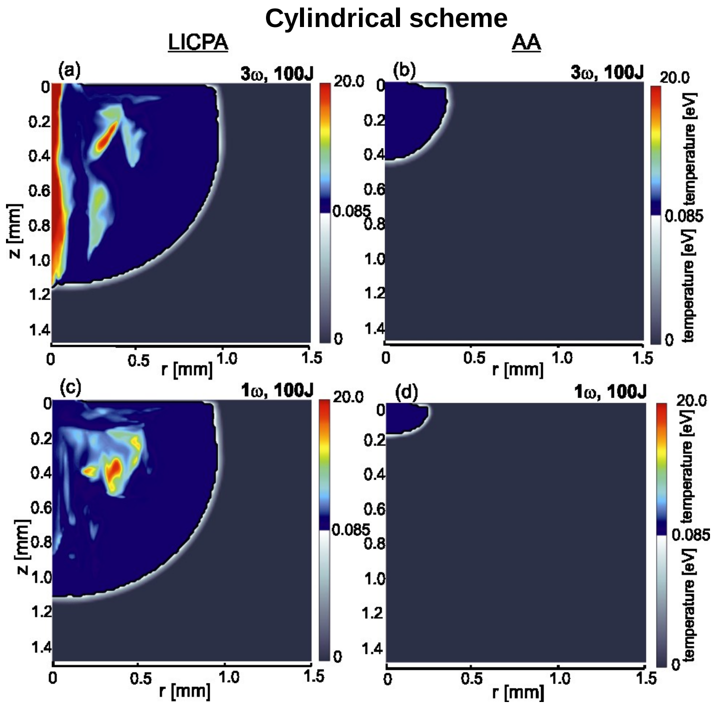
(a) Experiment



(b) 2D hydro simulations for cylindrical scheme

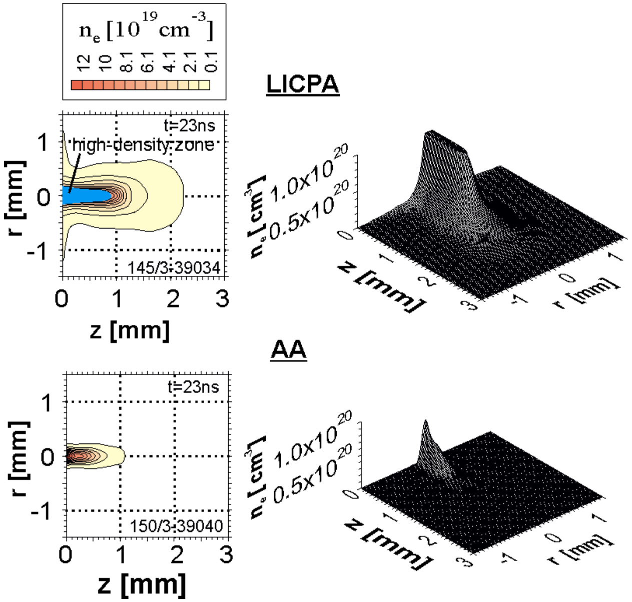


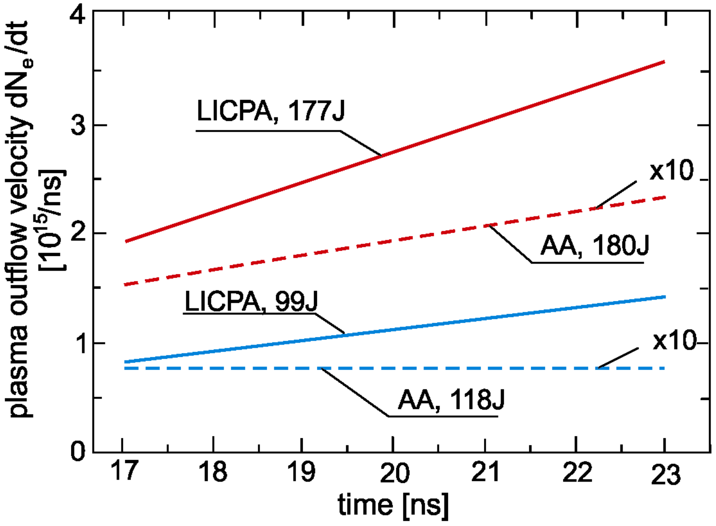
Both in the experiment and the simulations the craters produced in the LICPA scheme are much bigger than the ones in the AA scheme ⇒ kinetic energy of the projectile accelerated by LICPA is much higher than in the case of AA.

Badziak et al., Phys. Plasmas ***19****, 053105 (2012)*

LICPA Experiment at PALS

The electron isodensitograms and the space profiles of electron distributions for the plasma flowing out of the channel in the LICPA and AA cylindrical schemes as well as the plasma outflow velocity as a function of time.



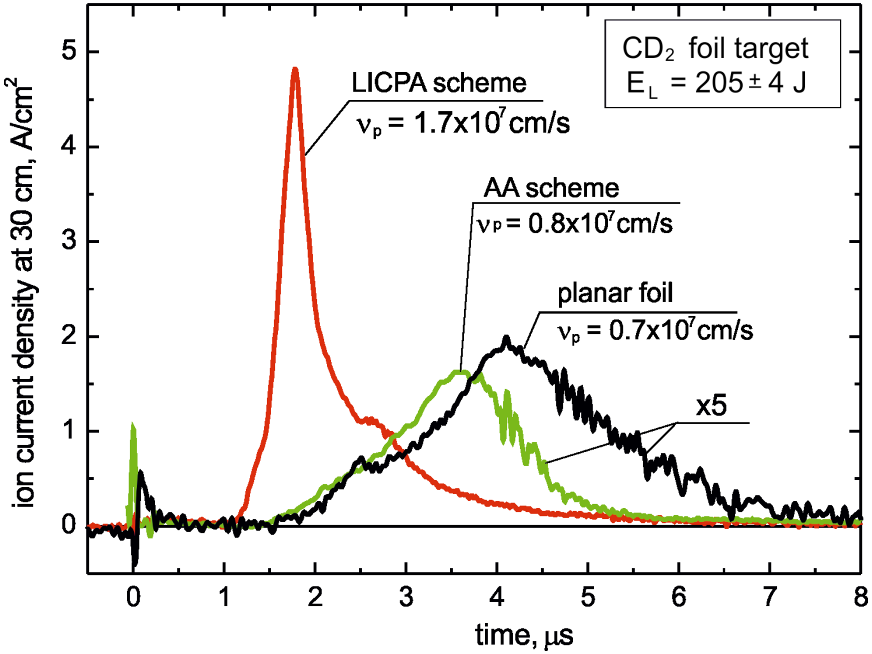


The plasma accelerated by LICPA is denser, carries much more electrons and ions and the plasma outflow velocity is by more than a factor 15 higher than in the case of AA.

Badziak et al., Phys. Plasmas ***19****, 053105 (2012)*

LICPA Experiment at PALS

The ion current density of plasma accelerated in the cylindrical LICPA scheme, AA scheme and planar foil target and measured on the 3ω laser beam axis at the long distance (30cm) from the plasma source



$$\bar{E}_i^{LICPA} \approx 4.5 \bar{E}_i^{AA}$$

$$j_i^{LICPA} \approx 15\, j_i^{AA}$$

$$I_i^{LICPA} \geq 30\, I_i^{AA}$$

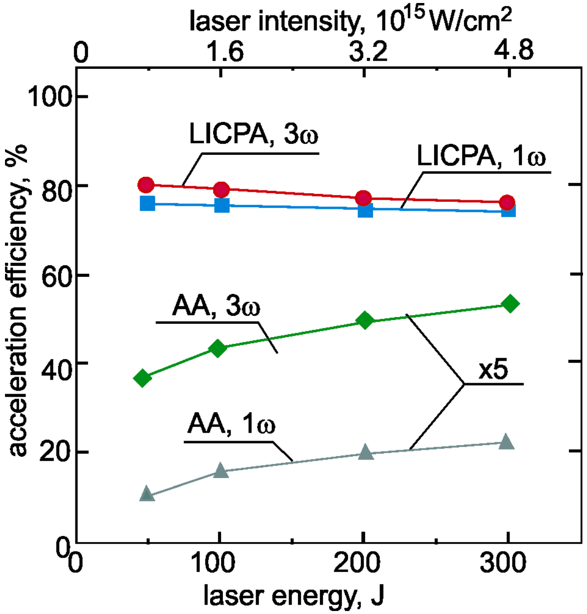
$$(I_i = (1/z)\, j\bar{E}_i)$$

The plasma accelerated in the LICPA scheme is significantly faster, more collimated and its ion current density is (at least) a factor 10 and intensity a factor 30 higher than in the case of AA scheme or planar target.

Badziak et al., Phys. Plasmas ***19****, 053105 (2012)*

LICPA Experiment at PALS

The acceleration efficiency of plasma projectiles driven in the LICPA and AA cylindrical schemes as a function of laser energy: the result of 2D hydro simulations for the conditions corresponding to those in the experiment.
CH target, $L_T = 20\ \mu m$, $L_{Ch} = 2$ mm, $d_{Ch} = 0.3$mm.



The acceleration efficiency in the LICPA scheme depends weakly on the laser energy and wavelength and is 7 to 11 times higher for 3ω and 16 to 34 times higher for 1ω than that for the AA scheme.

The acceleration efficiency in the LICPA scheme reaches the values in excess of 70% both for the 3ω and the 1ω laser driver.

Badziak et al., Phys. Plasmas ***19****, 053105 (2012)*

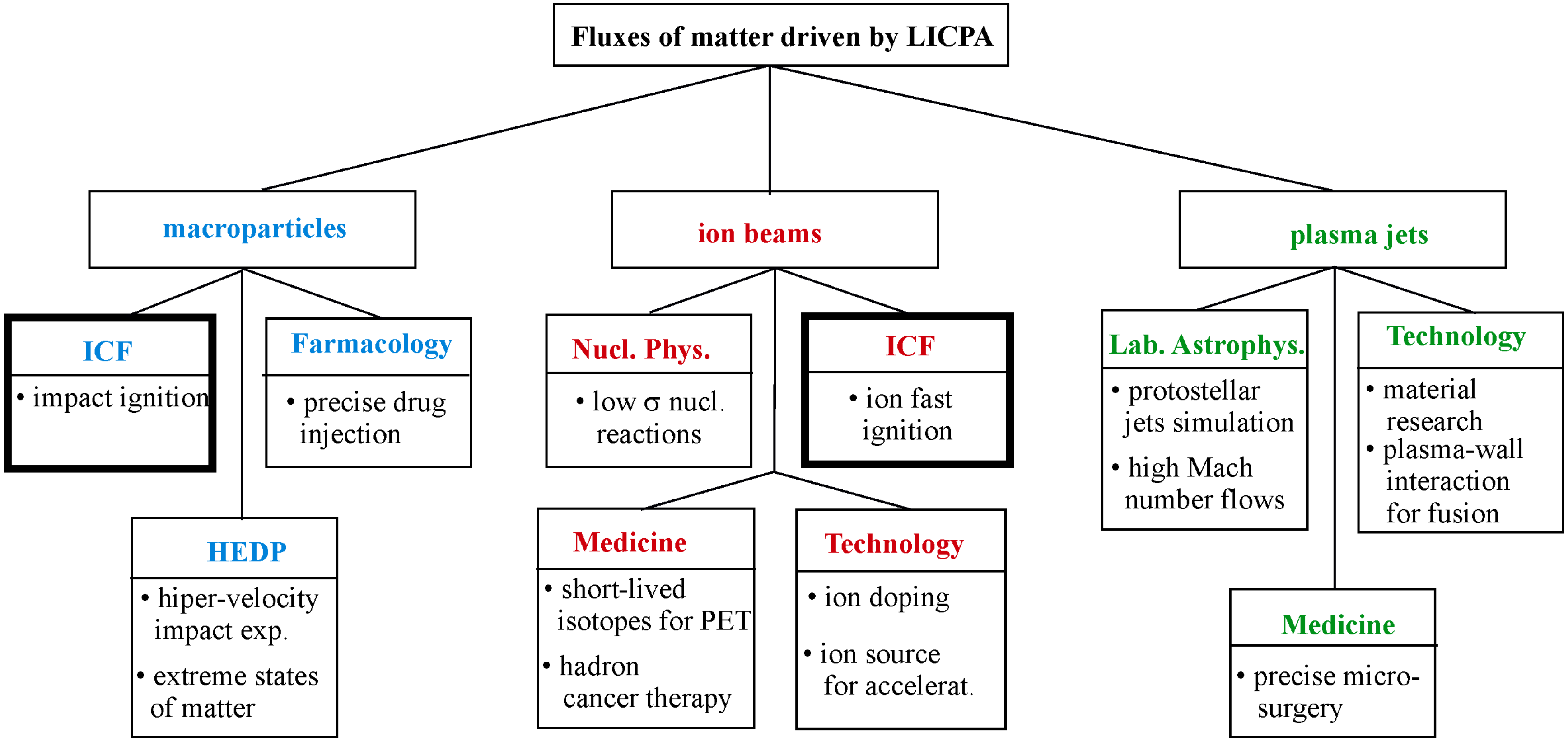
LICPA Experiment at PALS

Summary

- Both measurements using various diagnostics and 2D hydro simulations prove that the hydrodynamic LICPA accelerator can produce fast and dense plasma projectiles with the energetic efficiency up to an order of magnitude higher than in the case of ablative acceleration (AA).

- The efficiency of the hydrodynamic LICPA accelerator weakly depends on the laser wavelength (as opposite to AA) and both for the long-wavelength (NIR) and the short-wavelength (VIS, UV) laser drivers can reach values well above **50%**.

Potential Applications of Intense Fluxes of Matter Produced in the LICPA Accelerator



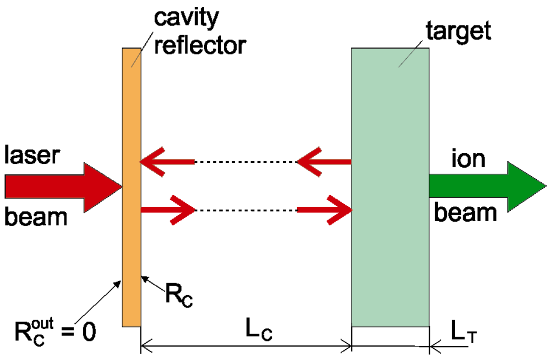
Fluxes of matter driven by LICPA

- **macroparticles**
  - **ICF**
    - impact ignition
  - **Farmacology**
    - precise drug injection
  - **HEDP**
    - hiper-velocity impact exp.
    - extreme states of matter
- **ion beams**
  - **Nucl. Phys.**
    - low σ nucl. reactions
  - **ICF**
    - ion fast ignition
  - **Medicine**
    - short-lived isotopes for PET
    - hadron cancer therapy
  - **Technology**
    - ion doping
    - ion source for accelerat.
- **plasma jets**
  - **Lab. Astrophys.**
    - protostellar jets simulation
    - high Mach number flows
  - **Technology**
    - material research
    - plasma-wall interaction for fusion
  - **Medicine**
    - precise micro-surgery

The Photon Pressure-Driven LICPA Accelerator

1D Particle-In-Cell (PIC) Simulations of Ion Acceleration
Basic assumptions and conditions

A fully electromagnetic relativistic 1D PIC code was used to simulate generation of the plasma (ion) projectile in the LICPA scheme and in the conventional RPA scheme (without the cavity)



Target:

- H$^+$, Be^{4+}, C^{6+}, Al^{13+} and Au^{10+} plasma of realistic n_i, n_e
- thickness $L_T = 0.1 – 30\ \mu m$
- preplasma of $L_n = 0.25\ \mu m$

Laser beam:

- wavelength $\lambda = 1.06 \mu m$, $0.8 \mu m$ or $0.53 \mu m$
- pulse duration $\tau_L = 0.1 – 10$ ps
- intensity $I_L = 10^{19} – 10^{23}\ W/cm^2$
- linear or circular polarization

Cavity:

$L_C = 20 – 300\ \mu m$
$= \infty$ (no cavity)

$R_c = 0.64 – 0.9$

We investigated the effect of L_c, L_T, I_L and light polarization on the ion beam parameters and the laser-ions energy conversion efficiency (the plasma projectile acceleration efficiency)

Ion Acceleration in the Photon Pressure-Driven LICPA Accelerator

The generalized light-sail model for the LICPA accelerator

Given $e^{(j)}(w)$, the target speed after the j-th reflection is expressed as

$$\beta^{(j)}(w) = \left[(1+e^{(j)}(w))^2 - 1\right] / \left[(1+e^{(j)}(w))^2 + 1\right]$$

The target position $x^{(j)}(w)$ is then obtained from the formula

$$x^{(j)}(w) = x^{(j-1)}(w_{j-1}) + \int_{w_{j-1}}^{w} \frac{\beta^{(j)}(w')}{1-\beta^{(j)}(w')}\, dw'$$

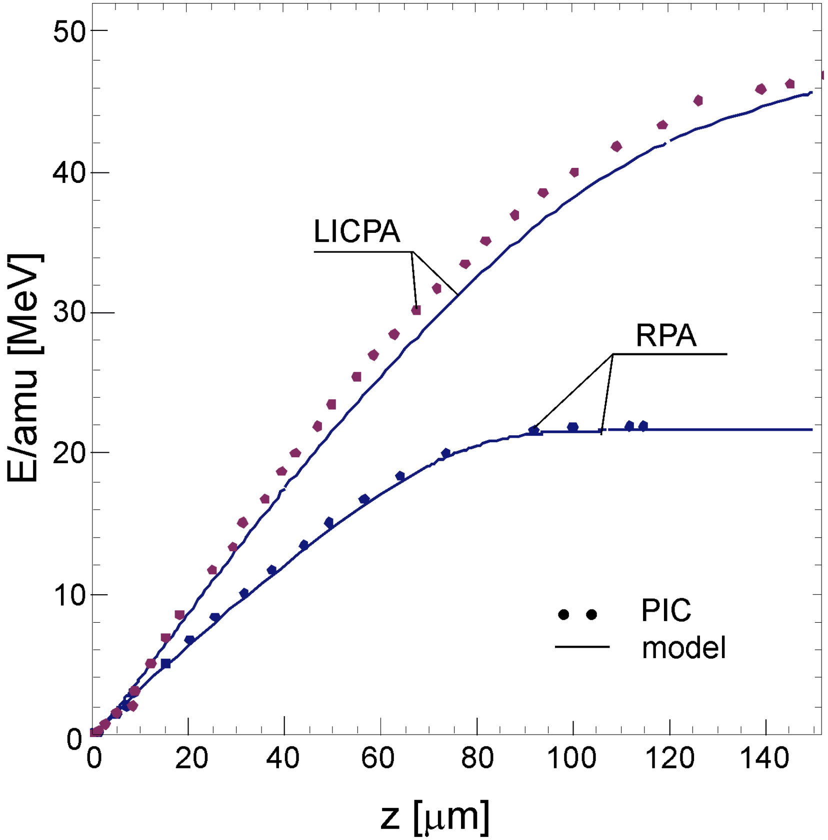
The energy deposition in the next stage is then given by

$$e^{(j+1)}(w) = e^{(j)}(w_j) + \frac{2}{\rho d c^3} \int_{w_j}^{w} I({w'}/{c})\, dw' + R_c \times \frac{e^{(j)}(w^{(j)}(w)) - e^{(j)}(w_{j-1}))}{(1+e^{(j)}(w^{(j)}(w)))(1+e^{(j)}((w_{j-1})))}$$

The function $w^{(j)}(w)$ gives the value of the retarded time from the interval $[w_{j-1}, w_j]$ characterizing the ray which after reflection from the accelerating foil strikes the inner cavity wall at the instant w belonging to the interval $[w_j, w_{j+1}]$.

Ion Acceleration in the Photon Pressure-Driven LICPA Accelerator

A comparison of the PIC simulations and the generalized LS model



C^{6+} ions, L_T= 2μm

I_L= 2.5 × 10^{21}W/ cm^2, τ_L = 2ps,

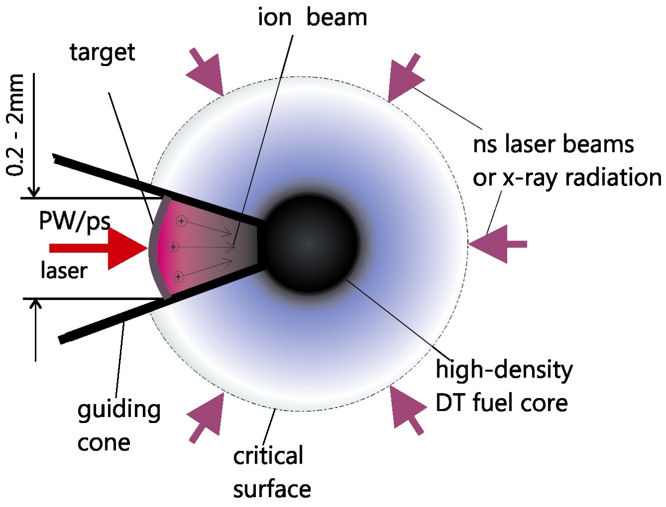
R_c= 0.64, L_c =80μm or L_c = ∞

The mean carbon ion energy per amu as a function of the acceleration length, as predicted by the 1D PIC simulation for the conventional RPA scheme (lower set of dots) and for the LICPA scheme with cavity length of 80 μm (upper set of dots). Continuous lines indicate predictions of the generalized light-sail model.

An **excellent agreement** between the PIC simulations and the model can be seen

Ion Fast Ignition

Scheme for IFI



Requirements for an ion beam:

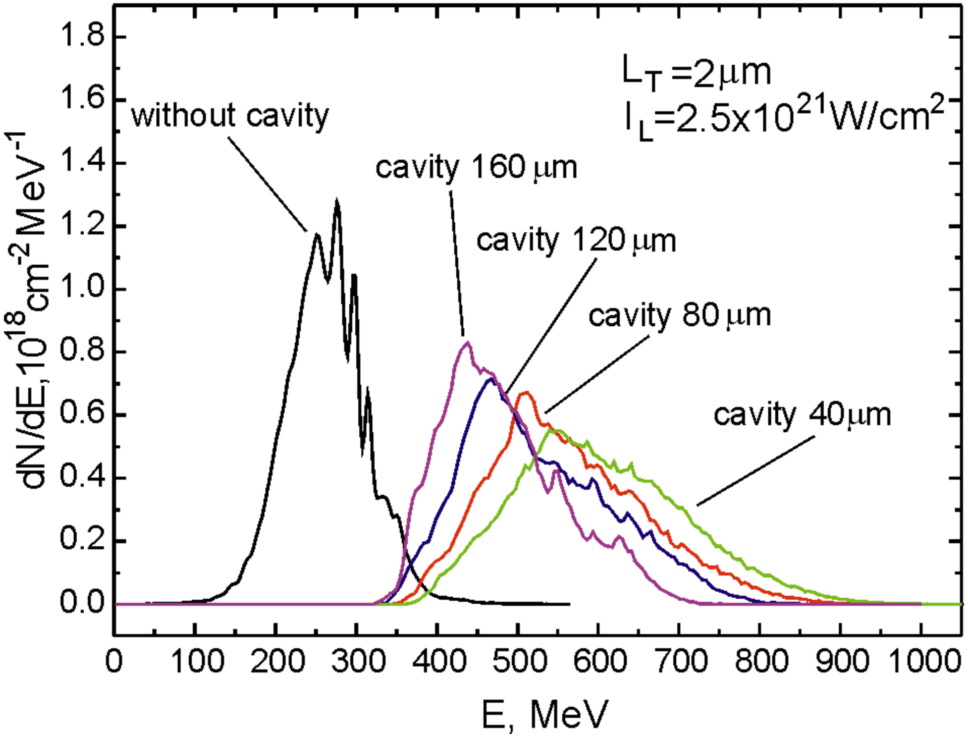
(at $\rho \approx$ 300 g /cm^3)

• beam energy	15 – 20 kJ
• mean ion energy	10 – 50 MeV/amu
• beam intensity	**≥ 10^{20} W/cm^2**
• beam fluence	**≥ 1 GJ/cm^2**
• pulse duration	5 – 20 ps
• beam power	1 – 4 PW
• beam size	≤ 40 μm
• ion production efficiency	**≥ 15%**

Acceleration of Carbon Ions in the LICPA Accelerator

Energy spectra of ions accelerated in the conventional RPA scheme (without cavity) and in the LICPA accelerator of various cavity lengths.

$R_c = 0.64$, $\tau_L = 2$ps, circular polarization,



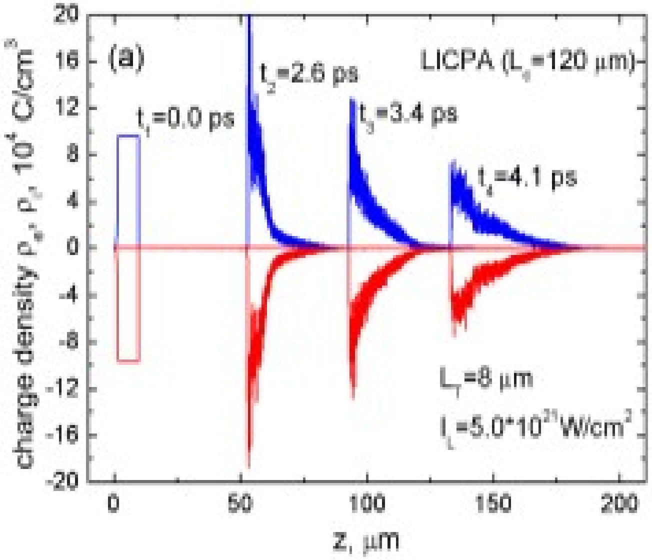
Both RPA and LICPA produces an ion beam of relatively narrow ion energy spectrum but the mean ion energy for LICPA is a factor 2 higher than that for RPA.

Acceleration of Carbon Ions in the LICPA Accelerator

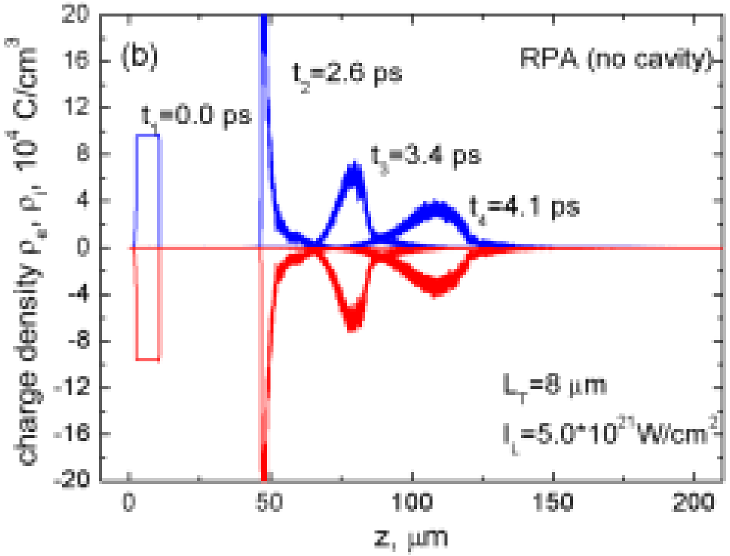
Snapshots of the ion (ρ_i) and electron (ρ_e) charge density distributions for carbon ion beams produced in the LICPA accelerator and in the conventional RPA scheme

L_T = 8μm, I_L = 5 x 10^{21} W/cm^2, τ_L = 2ps, circular polarization, R_c = 0.64

LICPA



RPA



The ion (plasma) bunch produced by LICPA is faster, denser and more compact than that produced by RPA

Acceleration of Carbon Ions in the LICPA Accelerator

The ion beam intensity and fluence as a function of laser intensity for ion beams produced by LICPA or RPA

$L_T = 8\mu m$, $L_c = 120\mu m$, $R_c = 0.64$, $\tau_L = 2ps$, circular polarization,

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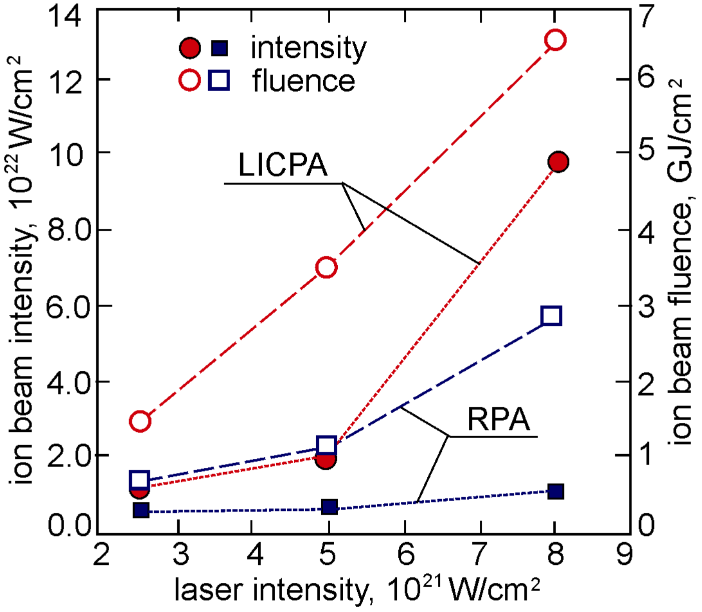
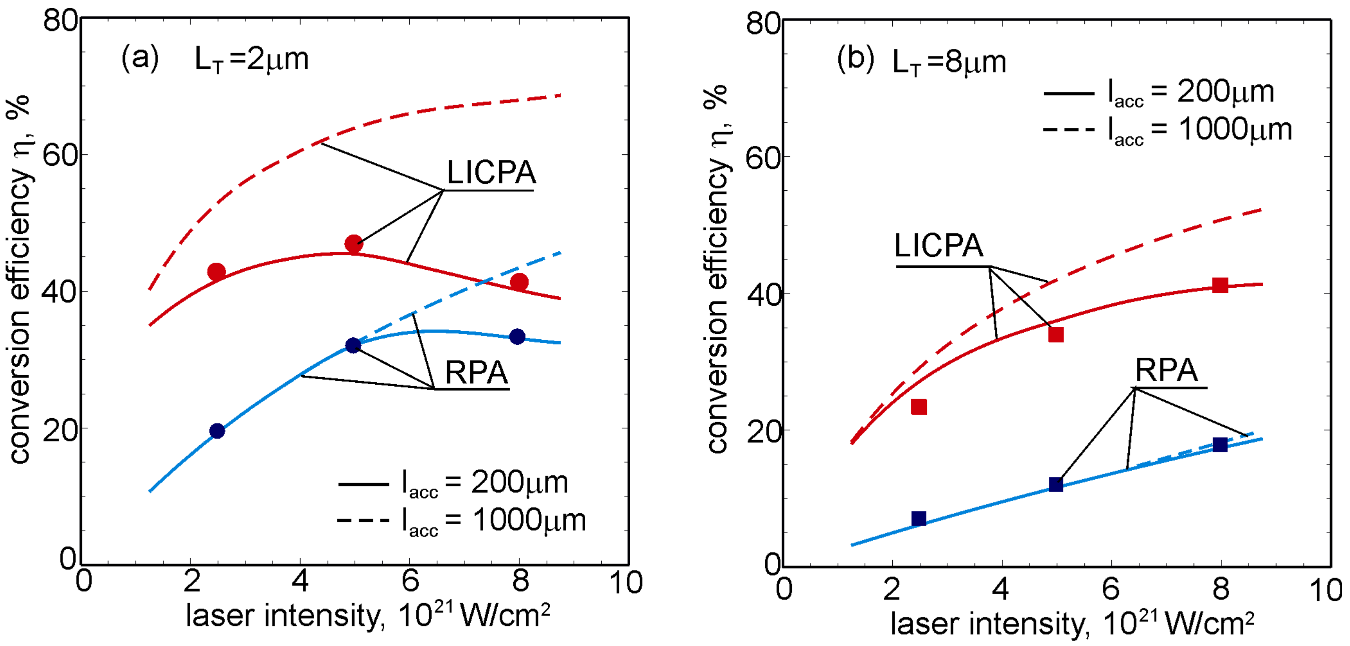


The beam intensity is a factor 10 higher and the beam fluence a factor 2 – 4 higher for LICPA than those for RPA

Acceleration of Carbon Ions in the LICPA Accelerator

Laser-ions energy conversion efficiency as a function of laser intensity as predicted by the GLS model (solid and dashed lines) and PIC simulations (dots)

L_c= 120μm, R_c = 0.64 , τ_L= 2ps, circular polarization,



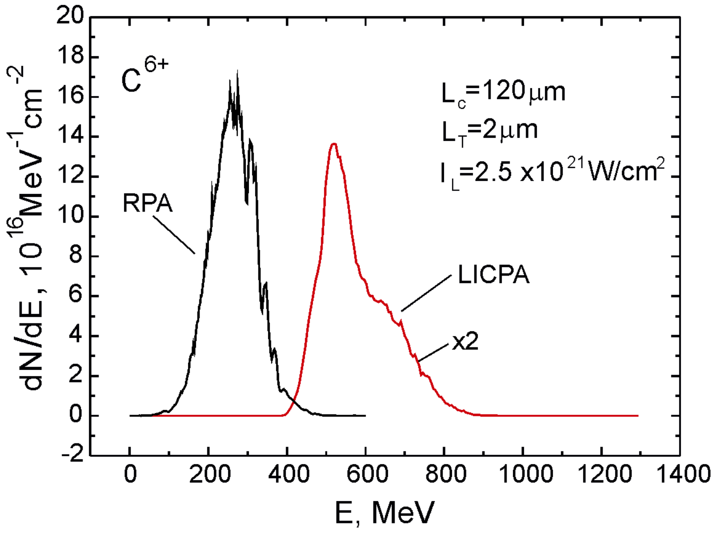
The conversion efficiency is higher for the thinner target for both LICPA and RPA but the ratio $R_\eta = \eta_{LICPA} / \eta_{RPA}$ is higher for the thicker target.

In general, the ratio R_η is the higher, the higher is mass (areal density) of the target.

Acceleration of Carbon Ions in the LICPA Accelerator

Parameters of carbon ion beams produced in the LICPA accelerator and the conventional RPA scheme

$E_L = 100\text{kJ}$, $\tau_L = 2\text{ps}$, $d_L = 50\mu\text{m}$, $L_c = 120\mu\text{m}$, $R_c = 0.64$, $L_T = 2\mu\text{m}$, $l_{acc} = 200\mu\text{m}$



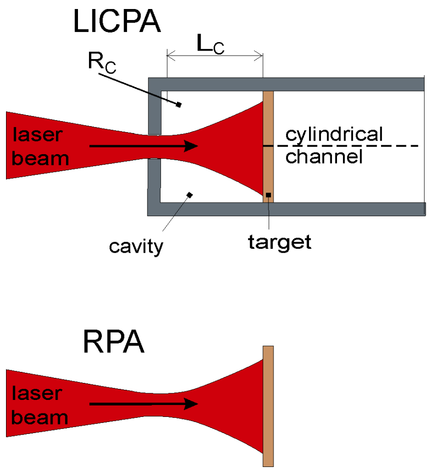
	RPA	LICPA
$\eta = E_b/E_L$,%	20	43
$\bar{E}_i$, MeV	260	580
$\Delta E_i/\bar{E}_i$	0.35	0.33
F_b, GJ/cm^2	0.96	2.1
I_i, 10^{22} W/cm^2	0.6	3.5

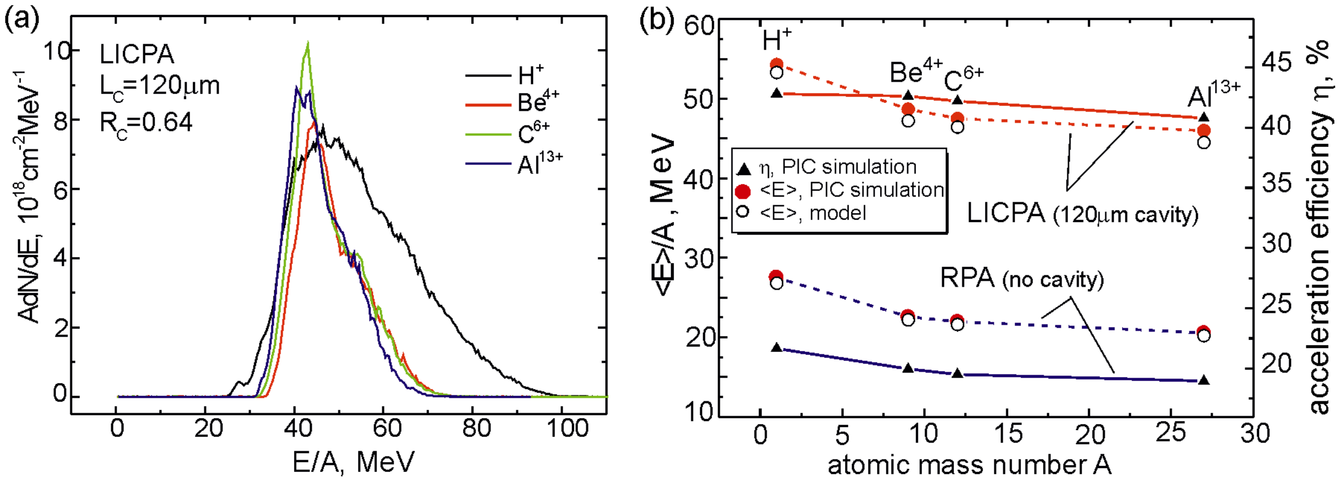
Assuming that at least 50% of the ion beam energy is deposited to the compressed (≥ 300g/cm^3) DT target, the ion beam produced by LICPA meets fairly well the requirements for the target ignition while parameters of the RPA beam are below the ignition threshold.

Acceleration of Ion in the LICPA Accelerator

The energy spectrum of various ions accelerated in the LICPA accelerator as well as a comparison of the mean ion energy and the laser-ions energy conversion efficiency for LICPA and the conventional RPA scheme – 1D PIC simulations.

$I_L = 2.5 \times 10^{21}$ W/cm^2, τ_L=2ps, circular polarisation; the areal mass density $\sigma_H \approx \sigma_{Be} \approx \sigma_C \approx \sigma_{Al}$.





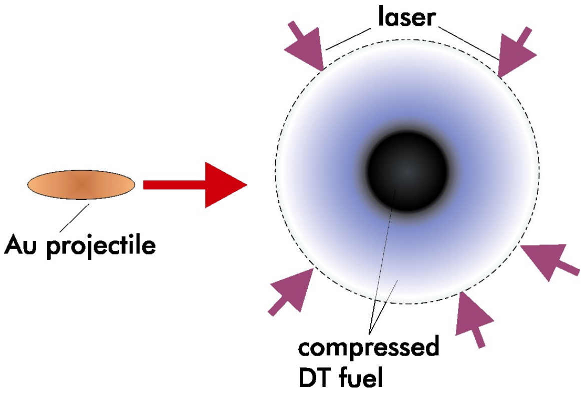
For all considered ions the mean ion energy and the conversion efficiency for LICPA are a factor 2 higher than those for the conventional scheme in spite of the conservative assumptions on the cavity parameters.

In the LICPA accelerator the conversion efficiency attains about 40% and the ion beam parameters (the mean energy, intensity, fluence) meet the FI requirements.

Impact Ignition Fusion

Basic schemes

IIF using a high-Z projectile
(Caruso and Pais, 1996)



$\rho_{DT} \sim 200 g/cm^3$

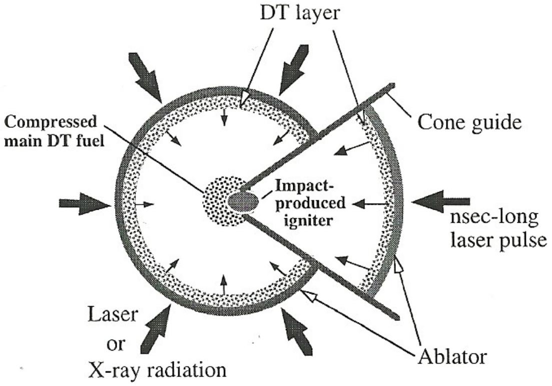
$\rho_p \approx \rho_s^{Au}$ (final $\rho_p \sim 50\rho_s^{Au}$)

$m_p \approx 1\mu g$

$v_p \approx$ 5000 km/s

Accelerator ? ?

IIF using a DT plasma projectile accelerated by laser plasma ablation inside a guiding cane
(Murakami and Nagatomo, 2005)



$\rho_{DT} \sim 200 \sim 300 g/cm^3$

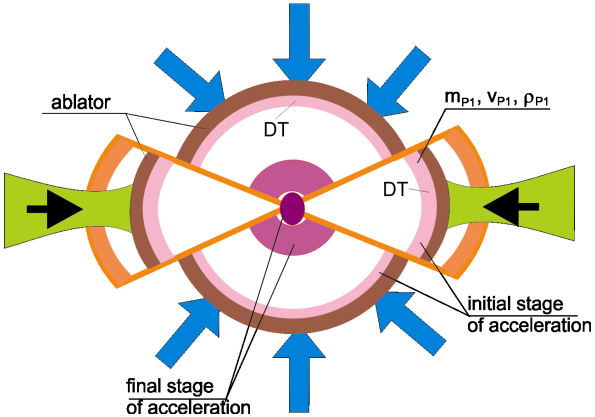
$\rho_p \approx 100\ \rho_s^{DT}$

$m_p \approx 30\mu g$

$v_p \approx$ 1500 km/s

Laser driver (for the projectile):
$E_L \approx$ 200kJ, $\tau_L \approx$ 5ns

IIF using two DT plasma projectiles driven in the LICPA accelerators
(Badziak et al.., 2009)



$\rho_{DT} \sim 200 g/cm^3$

$\rho_p \approx 50\ \rho_s^{DT}$

$m_p \approx 50\mu g$

$v_p \approx$ 800 – 1000 km/s

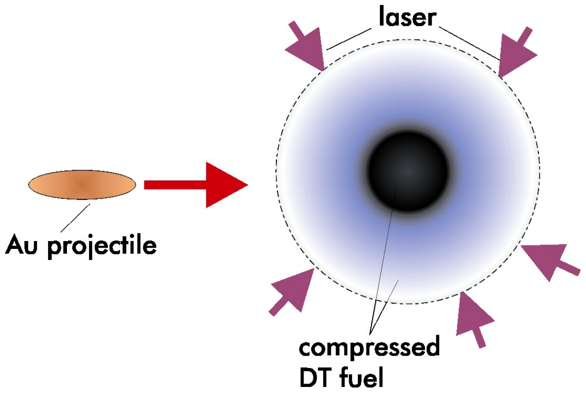
Laser driver (for 1 projectile):
$E_L \approx$ 50kJ, $\tau_L \approx$ 1ns

Acceleration of a Heavy Macroparticle in the LICPA Accelerator

Requirements for a macroparticle and input parameters for PIC simulations

IIF using a high-Z projectile

(Caruso and Pais, 1996)



Requirements for Au projectile:

mass $m_p \sim 1 \mu g$

density $\rho_p \sim \rho_s$ (before collision)

velocity $v_p \geq 5 \times 10^8$ cm/s

fluence $F_p \geq 500 MJ/cm^2$

Input parameters for PIC simulations

Target:

Au^{10+} of $\rho = 19.3 \, g/cm^3$

mass $m_p = 0.5 \; \mu g$

thickness $L_T = 5 \; \mu m$ (σ ekwivalent to $L_T \approx 1 mm$ for H^+)

preplasma $L_n = 0.25 \; \mu m$

Laser beam:

wavelength $\lambda = 1.06 \; \mu m$

pulse duration $\tau_L = 10$ ps, 5 ps, 2.5 ps (super-Gaussion)

energy $E_L = 100$ kJ, 200 kJ, 300 kJ

diameter $d_L = 80 \; \mu m$

circular polarization

Cavity:

Length $L_c = 300 \mu m$ or ∞ (no cavity)

reflection coeff. $R_c = 0.75$

Acceleration of a Heavy Macroparticle in the LICPA Accelerator

Snapshots of the space distributions of ion (ρ_i) and electron (ρ_e) densities for Au macroparticle driven by LICPA as well as the energy spectrum of Au ions

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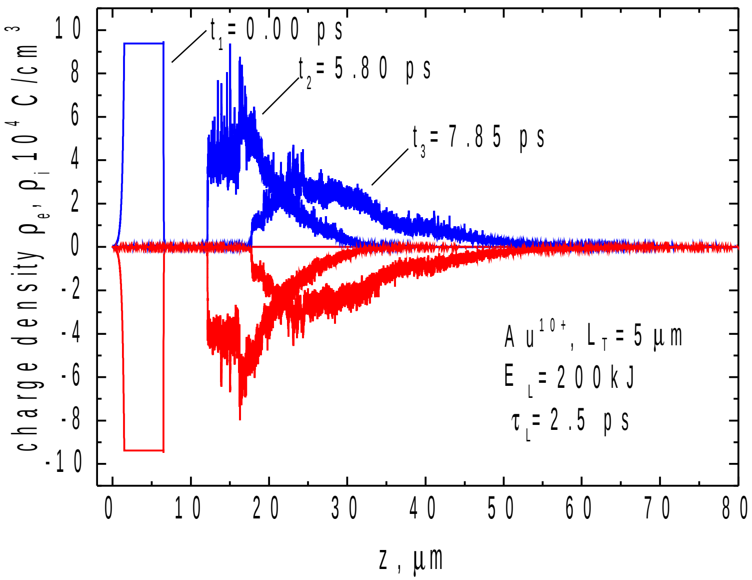
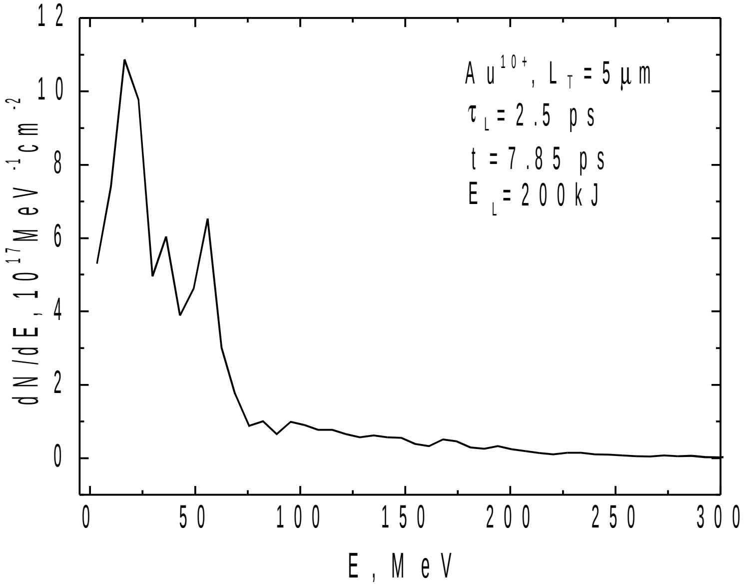
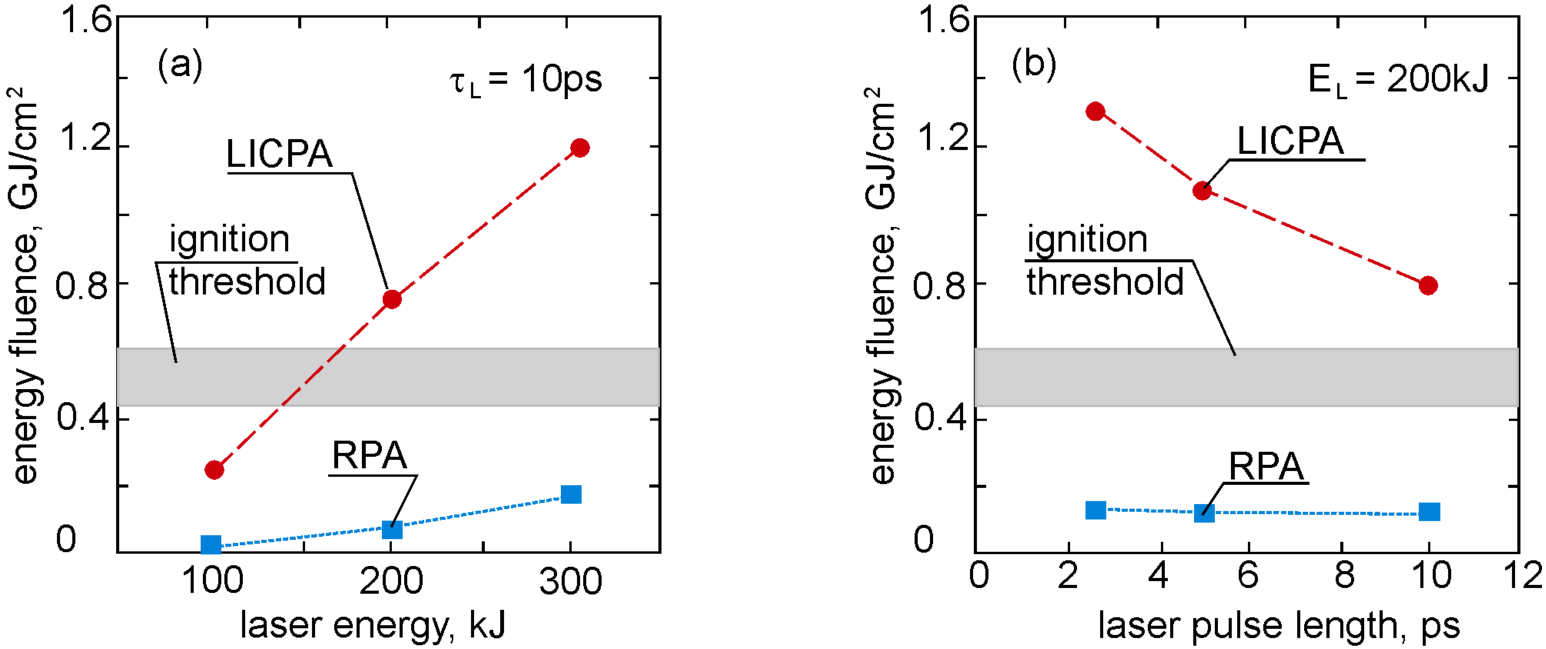




The macroparticle reaches velocity above 5 x 10^8 cm/s, however the energy spectrum of Au ions is broad.

Acceleration of a Heavy Macroparticle in the LICPA Accelerator

Energy fluence of Au macroparticle driven by LICPA or RPA
as a function of laser energy (a) and the laser pulse length (b)



The energy fluence of macroparticle driven by LICPA reaches the ignition threshold at laser energy ~150kJ while parameters of the macroparticle driven by RPA are well below the threshold even at much higher laser energies.

Summary and conclusions

- PIC simulations and the generalized LS model have shown that the photon pressure-driven LICPA accelerator can be an efficient tool for the production of high-energy, ultraintense ion beams of near solid-state density and quasi-monoenergetic ion energy spectrum.

- The LICPA accelerator using a picosecond 100 kJ laser driver can produce – with tens of percent efficiency – light ion beams of mean ion energies ~ 40 – 50 MeV/amu, energy fluencies > 1GJ/cm^2 and intensities ≥ 10^{21} W/cm^2; the beam parameters meet fairly well the FI requirements.

- The laser-ions energy conversion efficiency for LICPA is a factor 2 or more higher than that for RPA and the ratio of the efficiencies $R_\eta = \eta_{LICPA} / \eta_{RPA}$ increases with an increase in the target mass.

- The LICPA accelerator can efficiently ($\eta \geq 10\%$) accelerate very heavy (~ 1μg) macroparticles to high velocities ($>5\times10^8$cm/s) and the acceleration efficiency for LICPA is almost an order of magnitude higher than that for RPA.

- In particular, the LICPA accelerator using a multi-ps laser driver of energy ~ 150 kJ can accelerate a 0.5 μg Au macroparticle to velocities ~ 10^9 cm/s required for DT ignition in the IIF scenario of Caruso and Pais.