Fast ion ignition
with ultraintense laser pulses

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CELIA, U Bordeaux

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Outline

Motivation

Fast Ignition with energetic ions

- TNSA scheme with thin foils
- Ion acceleration in underdense plasmas, collisionless shocks
- RPA scheme in the hole-boring mode
  - Analytical estimates
  - 1D/ 2D PIC simulation results
  - Fast ignition requirements
- Cone-guided carbon acceleration
- Large-scale fusion pellet with *in-situ* DT acceleration

Conclusion

Fast Ignition in Inertial Fusion Energy production

M. Tabak et al., Phys. Plasmas 1994
M. Tabak et al., Fusion Science and Technology 2006

fuel gain in an isobaric configuration:

$$G = \phi Q M / (\eta E_{driver}), \quad \phi = \frac{h}{h + 7\,\mathrm{g\,cm^{-2}}}$$

$$\eta E_{driver} = E_{hs} + E_{M\,fuel}$$

$$E_{hs}[\mathrm{MJ}] = M_{hs} C_{\mathrm{v}} T_{hs} = \frac{4\pi}{3} \frac{h_{hs}^3}{\rho_{hs}^2} C_{\mathrm{v}} T_{hs}$$

$$E_{M\,fuel}[\mathrm{MJ}] = 0.3\,\alpha\,(M - M_{hs})\,\rho_{M\,fuel}^{2/3}$$

Ignition requirements for FI

S. Atzeni, Phys. Plasmas 1999

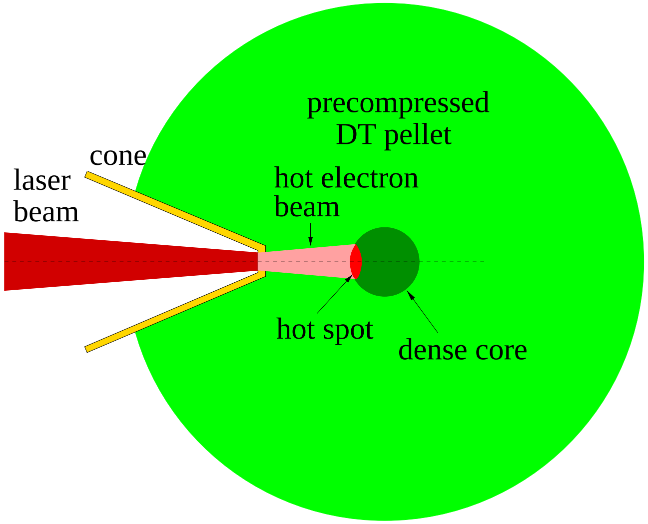
- Laser propagation in overcritical plasma: hole boring, relativ. transparency

high laser intensities to propagate over mm plasma length in 10 - 20 ps

- Cone-guided electron acceleration

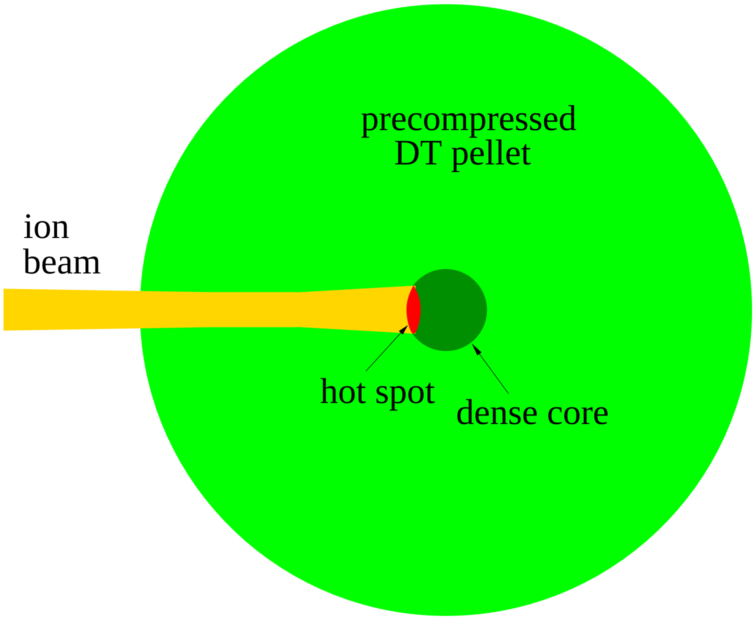
R. Kodama et al., Nature 2002
A. Debayle et al., J. Phys. Conf. Ser. 2010

higher coupling efficiency to e^-,
problems in transport to the compressed fuel
influence of the implosion process



Fast Ignition by laser-accelerated proton/ light ion beams

M. Roth et al., PRL 2001
V.Yu. Bychenkov et al., Plasma Phys. Rep. 2001
S. Atzeni et al., Nucl. Fusion 2002
M. Temporal et al., Phys. Plasmas 2002
J.F. Fernandes et al., Nucl. Fusion 2009



less deflection by atomic scatters, induc. fields
divergence < 10 mrad required
spread in energy → spread in arrival times

$$E_{ig} = 90\left(d_{\mathrm{mm}}\right)^{0.7}\left(\frac{\rho}{100\,\mathrm{g\,cm^{-2}}}\right)^{-1.3}\ \mathrm{kJ}$$

$$T_p = 1\text{ - }8\,\mathrm{MeV}$$

NOVA-Petawatt:

$$I_L = 5\times10^{20}\ \mathrm{W\,cm^{-2}},\ \ 60\ \mathrm{MeV\ protons}$$

$$\eta = 10\text{ - }20\,\%\,,\ \ \mathrm{emittence} < 0.004\ \mathrm{mm\ mrad}$$

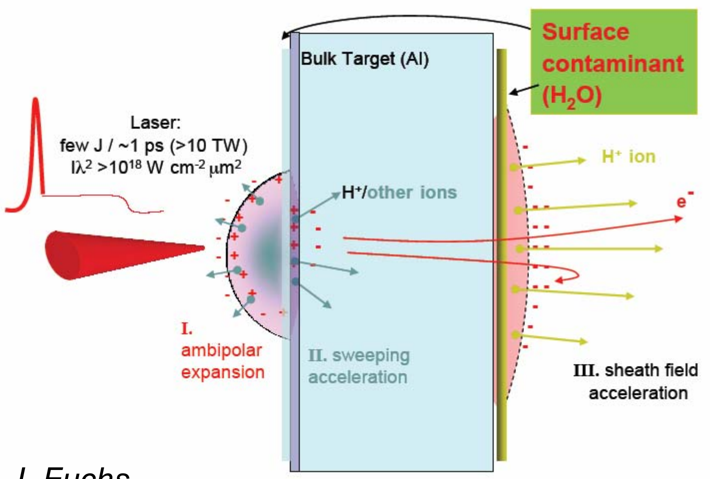
focused beams by shaped targets
focusability at high currents ?

$$\varepsilon_p = 10\ \mathrm{MeV},\ \ r_{hs} \sim 15\,\mu\mathrm{m},\ \ \tau_{dep} \sim 10\,\mathrm{ps}$$

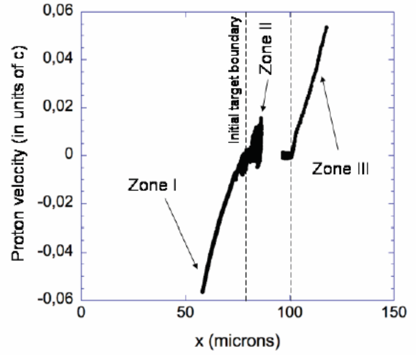
$$E_{pb} = 50\,\mathrm{kJ}\quad \rightarrow 10^{22}\,\mathrm{protons/cm^2}$$

TNSA of protons and light ions (foil targets)

Interaction scheme



*J. Fuchs,
HDR thesis 2010*



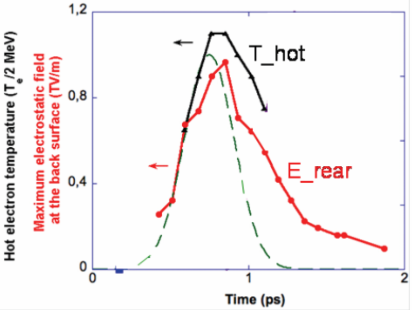
isothermal expansion

Gurevich 1966, Mora 2003

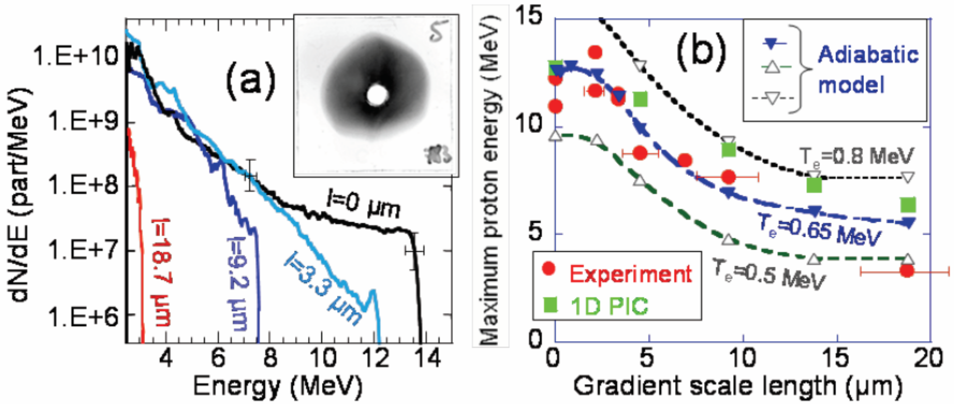
$$E_{\max} = 2\,Z\,T_h \left[\ln\left(t_p + \sqrt{1+t_p^2}\right)\right]^2,$$

$$t_p = \omega_{pi} t_{acc} / \sqrt{2e_N}$$

adiabatic cooling



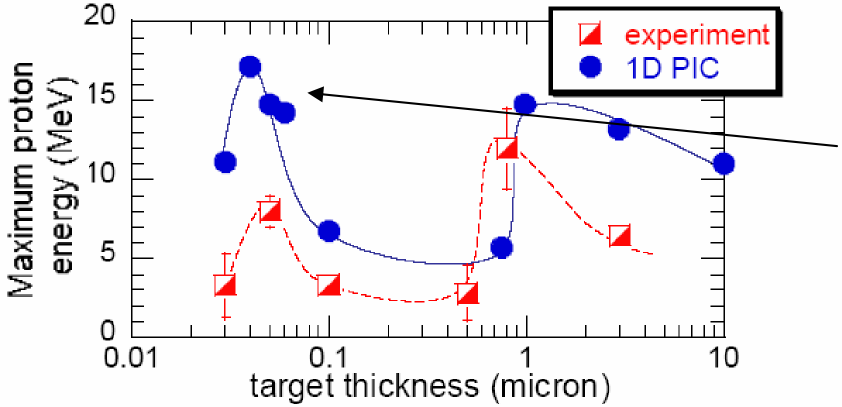
rear surface gradients



Ion acceleration from an underdense plasma

L. Willingale et al., PRL 2006

influence of: density gradients (length, shape, amplitude), laser pulse shape

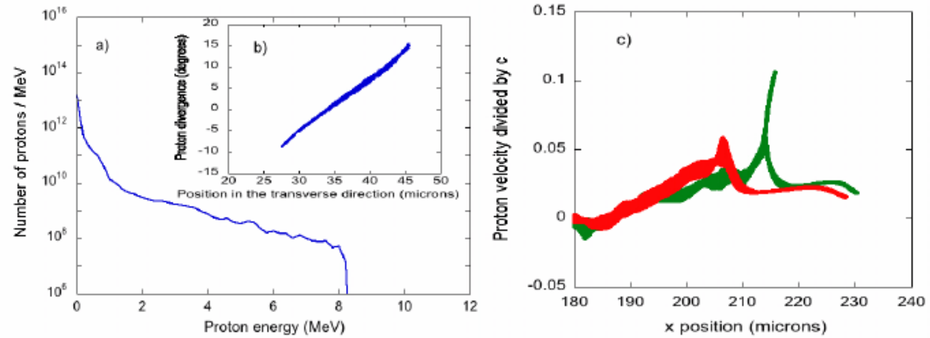


P. Antici et al., NJP 2009

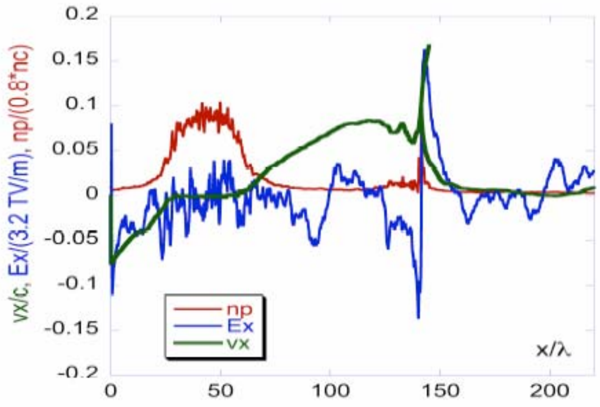
electron heating near the target rear surface

two steps of interaction:
1. electron heating → ion acc.
2. sufficient high ion velocities → reflection of upstreaming ions

collisionless electrostatic shock

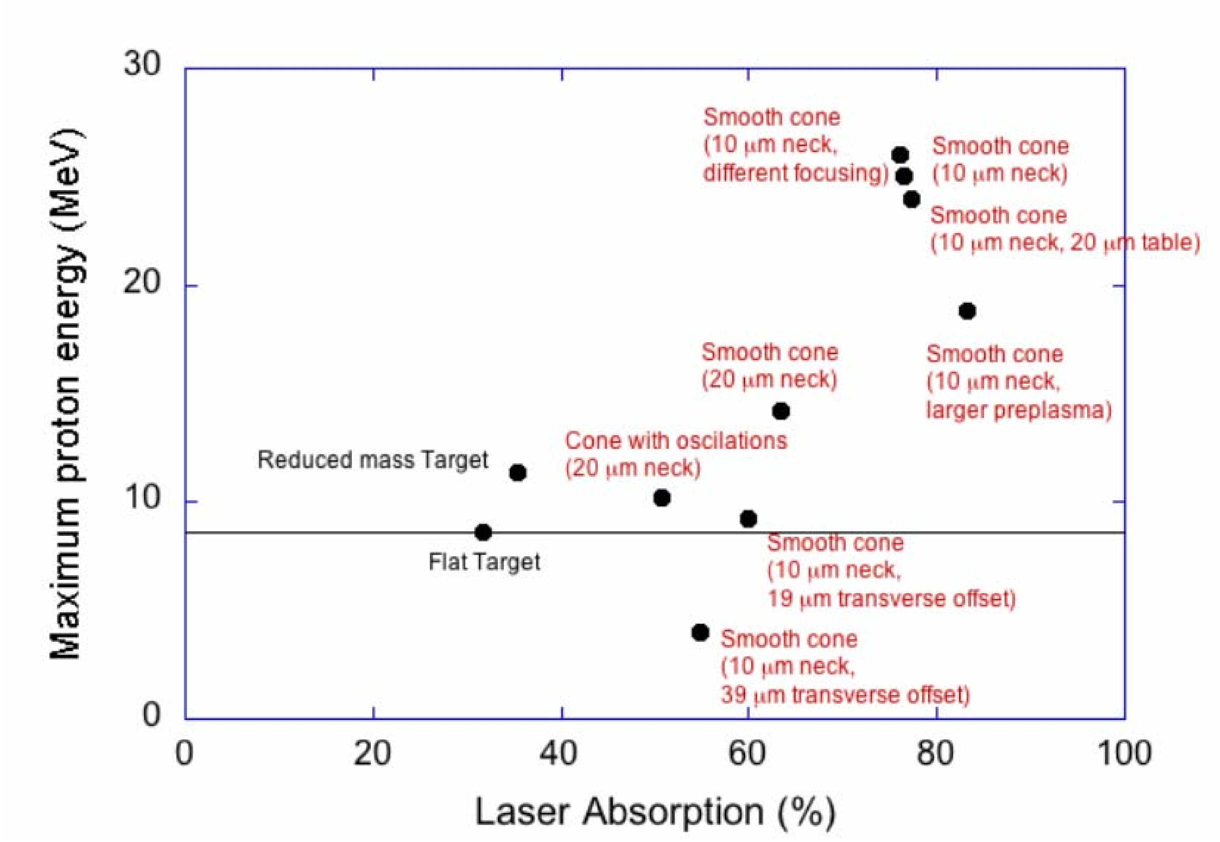


E. d'Humieres, 2010, 2011



Ion acceleration from foils at the tip of a cone

K. Flippo et al., Phys. Plasmas 2008

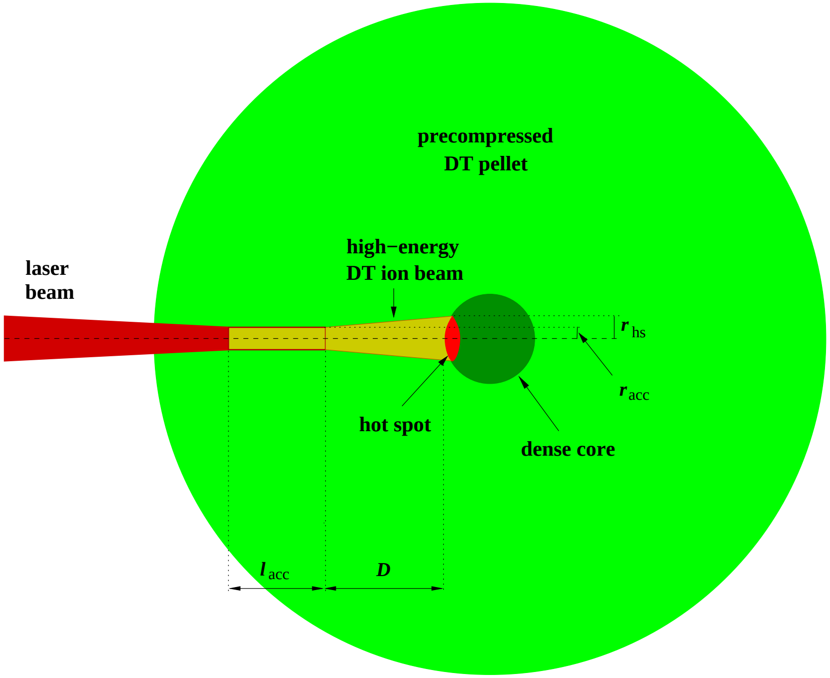


efficient laser absorption, higher T_h and N_h
curved tip surface: cone determines the beam characteristics, divergence control

Alternative fast ion ignition scheme

In-situ DT acceleration

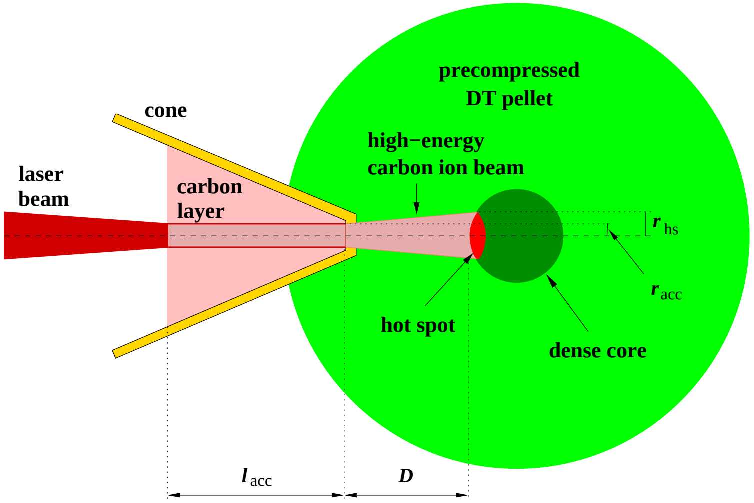
V. Tikhonchuk et al., Nucl. Fusion ***50****, , 045003 (2010)*



D.S. Clark and M. Tabak., Nuclear Fusion ***47****, 1147 (2007)*

Cone-guided carbon acceleration

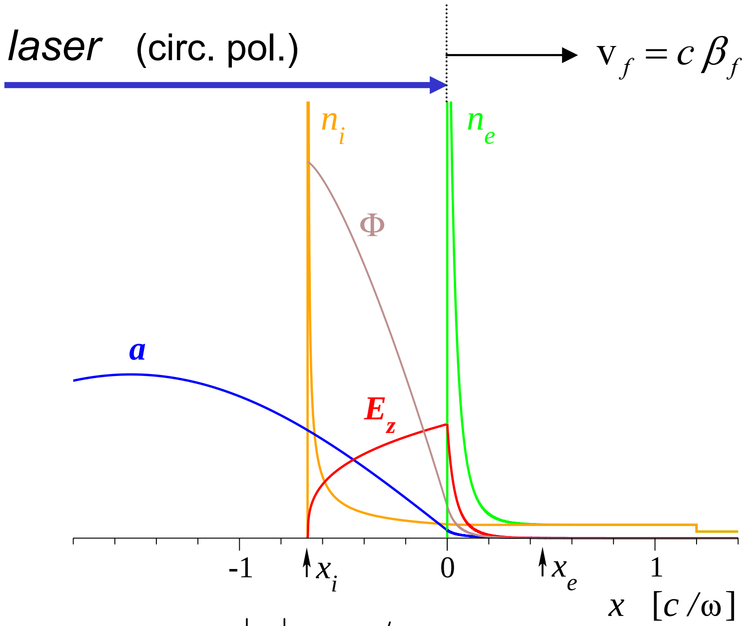
C. Regan et al., Plasma Phys. Control. Fusion ***53****, 045014 (2011)*



A. Debayle et al., J. Phys. Conf. Ser. ***244****, 022032 (2010)*

Analytical piston model

Quasi-stationary laser piston in overdense plasmas



$$|x_i| \sim v_f / \omega_{pi}$$

charge separation layer

$$\boxed{E_z = 2\,E_{\text{las}} \sqrt{\frac{1-\beta_f}{1+\beta_f}}}$$

momentum flux balance:
(in the moving frame MF**)**

$$\frac{2\,I_{\text{las}}}{c}\,\frac{1-\beta_f}{1+\beta_f} = 2\,\rho\,c^2\gamma_f^2\beta_f^2$$

$$\longrightarrow \quad \beta_f = \frac{B}{1+B}\,, \quad \boxed{B = \sqrt{I_{\text{las}}/\rho\,c^3}}$$

$$\text{LF}: \quad \varepsilon_i = 2 m_i c^2 \frac{B^2}{1+2B}\,, \quad 1 - R = \frac{2B}{1+2B}$$

main properties confirmed in PIC simulations

A. Robinson et al., Plasma Phys. Control. Fusion ***51****, 024004 (2009)*

N. Naumova et al., Phys. Rev. Lett. ***102****, 025002 (2009)*

T. Schlegel et al., Phys. Plasmas ***16****, 083103 (2009)*

Analytical piston model

Homogeneous plasma

$$\mathcal{E}_i = 2 m_i c^2 \frac{B^2}{1+2B}, \quad N_i = \frac{\rho}{m_i} l_{\mathrm{acc}}, \quad F_{\mathrm{acc}} = N_i \, \mathcal{E}_i, \quad \tau_{\mathrm{las}} = \frac{l_{\mathrm{acc}}}{B\,c}, \quad A_{\mathrm{acc}} = \frac{2B}{1+2B}$$

account for beam divergence:

$$F_{\mathrm{hs}} = \eta \frac{\mathcal{N}_i \mathcal{E}_i}{\pi r_{\mathrm{acc}}^2 l_{\mathrm{acc}}} \int_D^{D+l_{\mathrm{acc}}} \frac{d\xi}{\left(1 + \delta\theta\, \xi / r_{\mathrm{acc}}\right)^2} = \eta\, F_{\mathrm{acc}} \left[\left(1 + \delta\theta \frac{D}{r_{\mathrm{acc}}}\right) \left(1 + \delta\theta \frac{D + l_{\mathrm{acc}}}{r_{\mathrm{acc}}}\right) \right]^{-1}$$

Plasma density profile with a scale length *L*

$$N_i = \frac{L}{m_i} \left(\rho_{\max} - \rho_{\min}\right), \quad F_{\mathrm{acc}} = \frac{4\,L\,I_{\mathrm{las}}}{c} \ln\left(\frac{B_{\min}}{B_{\max}} \frac{1+2B_{\max}}{1+2B_{\min}} \right),$$

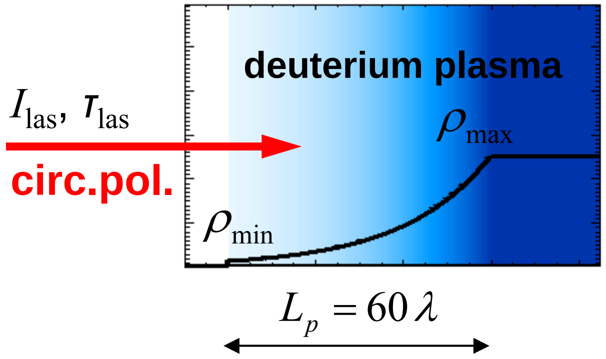
$$\left\langle \mathcal{E}_i \right\rangle = F_{\mathrm{acc}} / N_i, \quad \tau_{\mathrm{las}} = \frac{2L}{c} \left(\frac{1}{B_{\max}} - \frac{1}{B_{\min}} \right), \quad A_{\mathrm{acc}} = \frac{F_{\mathrm{acc}}}{I_{\mathrm{las}}\, \tau_{\mathrm{las}}}$$

1D PIC simulations

Simulation parameters:

$$I_{\text{las}} = 4\times10^{22}\,\text{W/cm}^2 \quad (a_0 = 100)$$

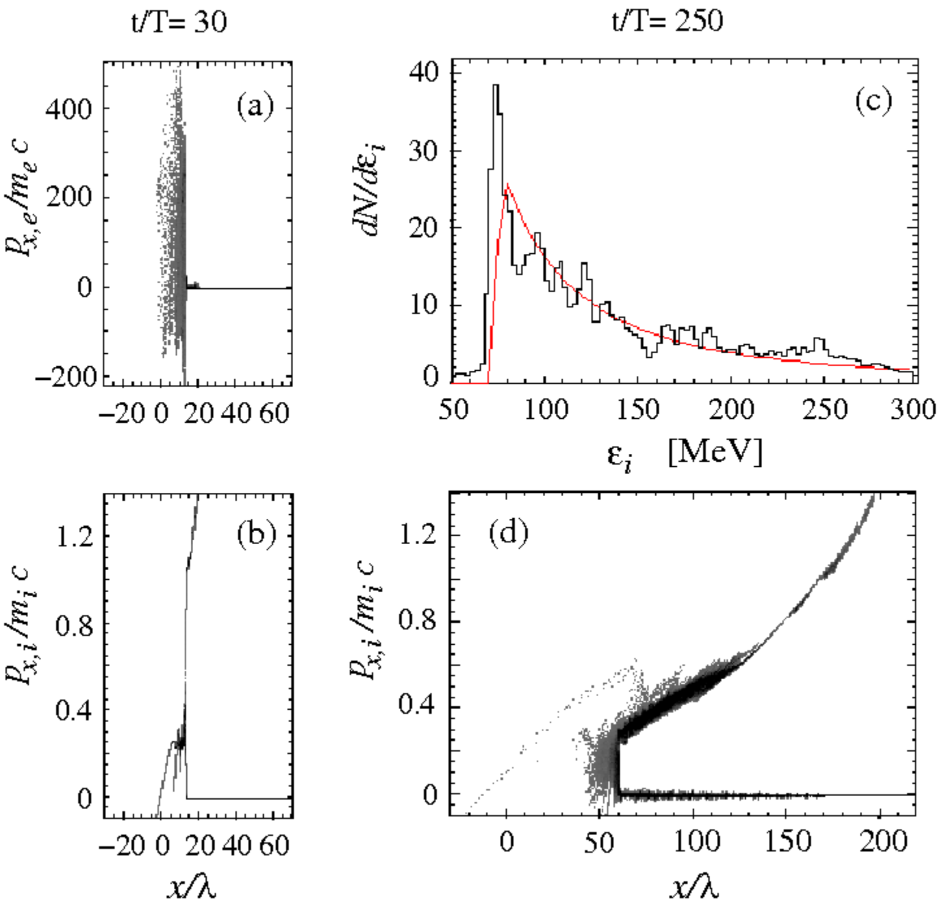
$$\lambda = 0.8\ \mu\text{m}$$



$$L = \frac{\rho}{d\rho/dx} = 20\,\lambda$$

efficiency: $F_{\varepsilon_i=(50-300)\,\text{MeV}} = 5.4\,\text{GJ/cm}^2$

$$A = F_i / F_{\text{las}} = 0.27$$



N. Naumova et al., PRL 2009

2D PIC simulations

Simulation parameters:

$$I_{\text{las}} = 4\times10^{22}\ \text{W/cm}^2 \quad (a_0 = 100)$$

$$\lambda = 0.8\ \mu\text{m}$$

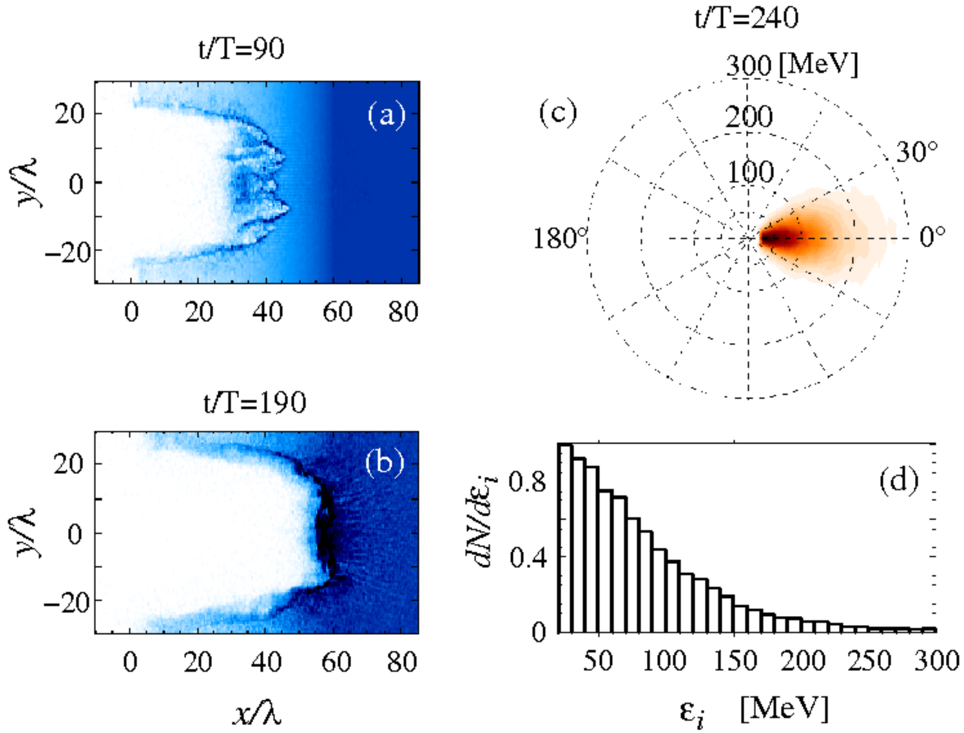
flat-top transverse laser-intensity profile: $\text{w} = 20\,\lambda$

deuterium plasma

clean and stable channel

small angular spread of ions

$$\varepsilon_i \geq 50\text{MeV}: \quad \theta \leq 5^\circ$$



N. Naumova et al., PRL 2009

Requirements for fast ignition application

- Circular laser polarization
- Overcritical plasma: $n_e / a_0 n_c \geq 1$
- Large number of accelerated ions, $\mathcal{N}_i \sim 10^{14} \div 10^{16}$, to provide: $F_{\mathrm{hs:ig}} \geq E_{\mathrm{ig}} / \pi r_{\mathrm{ig}}^2$
- Sufficiently small laser focus, $r_{\mathrm{acc}} < r_{\mathrm{ig}}$, because of ion beam divergence
- Rayleigh length of the laser pulse > acceleration length l_{acc}
- High laser contrast, flat transverse intensity profile

$\}$ for mono-energetic ion acceleration

IFI scheme design

1. Essential precompressed pellet parameters: $\rho_{\mathrm{max}}\ ,(\rho R)_{\mathrm{core}}\ ,\ L$

2. Ignition scaling laws $\longrightarrow$ $E_{\mathrm{ig}}\ , r_{\mathrm{ig}}\ , \tau_{\mathrm{ig}}$ *S. Atzeni, Phys. Plasmas* ***6****, 3316 (1999)*

3. Supposed density ratio of the acceleration zone, $\rho_{\mathrm{max}} / \rho_{\mathrm{min}}$, and D

   $\longrightarrow$ $l_{\mathrm{acc}}\ , \rho_{\mathrm{max}}\ , \rho_{\mathrm{min}}\ , N_i$

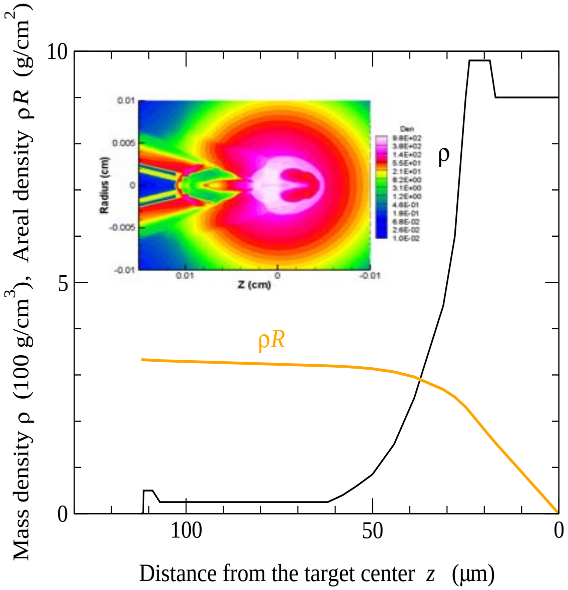
4. With a chosen laser intensity I_{las} $\longrightarrow$ $F_{\mathrm{acc}}\ , \langle \varepsilon_i \rangle$

5. Laser focal spot radius r_{acc} and ion beam divergence $\delta\theta$ determine F_{hs}

$$\eta\, F_{\mathrm{hs:ig}}\, \pi\, r_{\mathrm{ig}}^2 \propto E_{\mathrm{ig}}$$

6. Final estimate of $P_{\mathrm{las}}\ , \tau_{\mathrm{las}}\ , E_{\mathrm{las}}\ , A_{\mathrm{acc}}$

Cone-guided target



Approximate DT density profile: $(\rho R)_{\text{core}} \approx 3\,\text{g/cm}^2$

Carbon layer with $\rho = 0.2\,\text{g/cm}^3$

Scalings for ignition:

$$E_{\text{ig}} = 7\,\text{kJ},\ r_{\text{ig}} = 12\,\mu\text{m},\ \tau_{\text{ig}} = 14\,\text{ps}$$

$$\longrightarrow\ F_{\text{ig}} \approx 1.6\,\text{GJ/cm}^2$$

$$N_i = \frac{\rho}{m_i} l_{\text{acc}},\quad F_{\text{acc}} = N_i\,\varepsilon_i,$$

$$\tau_{\text{las}} = \frac{l_{\text{acc}}}{Bc},\quad A_{\text{acc}} = \frac{F_{\text{acc}}}{I_{\text{las}}\,\tau_{\text{las}}}$$

Estimate:

$$\varepsilon_i = 450\,\text{MeV} \ \longrightarrow\ I_{\text{las}} = 1.4\times10^{22}\,\text{W/cm}^2\ (a_0 \approx 60)$$

$$r_{\text{acc}} = 6\,\mu\text{m},\ l_{\text{acc}} = 200\,\mu\text{m}$$

$$\longrightarrow\ N_i = 2\times10^{20}\,\text{cm}^{-2},\ F_{\text{acc}} \approx 14\,\text{GJ/cm}^2$$

$$D = 60\,\mu\text{m},\ \delta\theta = 0.1:\ r_{\text{hs}}^2 \approx 11 r_{\text{acc}}^2,\ F_{\text{hs}} \approx 1.3\,\text{GJ/cm}^2$$

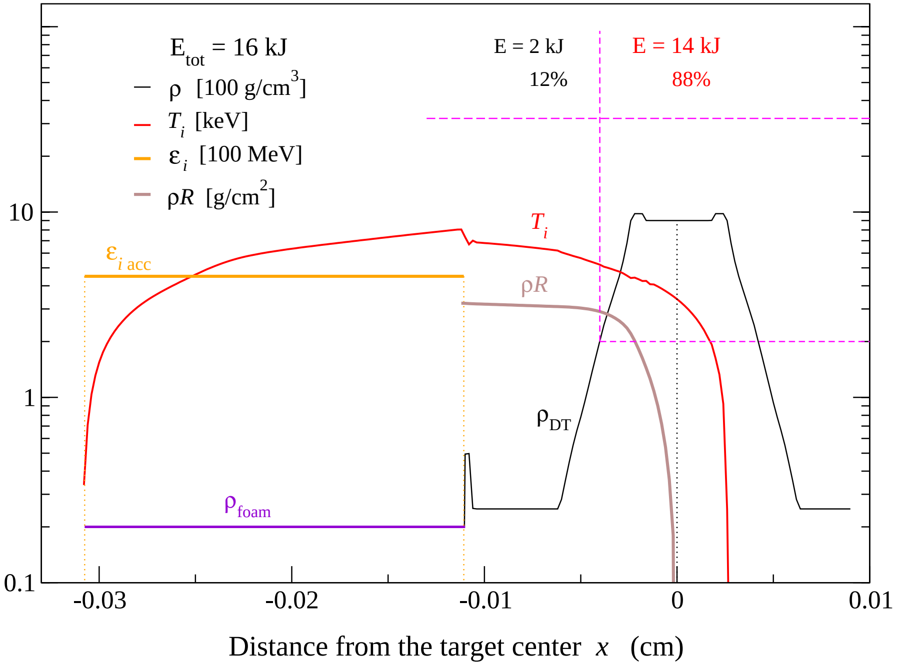
$$E_{\text{hs: ig}} = 5\,\text{kJ}\ (\eta = 0.8)\ \longrightarrow$$ **no ignition**

Higher directionality

$$\boxed{\delta\theta = 0.05} \longrightarrow F_{\mathrm{hs:ig}} = 3\,\mathrm{GJ/cm^2}$$

$$E_{\mathrm{hs:ig}} = 11\,\mathrm{kJ}\ \ (\eta = 0.8)$$

Profiles after ion stopping:
(*Trumpet code*)



successful ignition

$$P_{\mathrm{las}} = 16\,\mathrm{PW},\ \ \tau_{\mathrm{las}} = 4\,\mathrm{ps}$$

$$E_{\mathrm{las}} = 65\,\mathrm{kJ}$$

$$A_{\mathrm{acc}} \approx 25\%$$

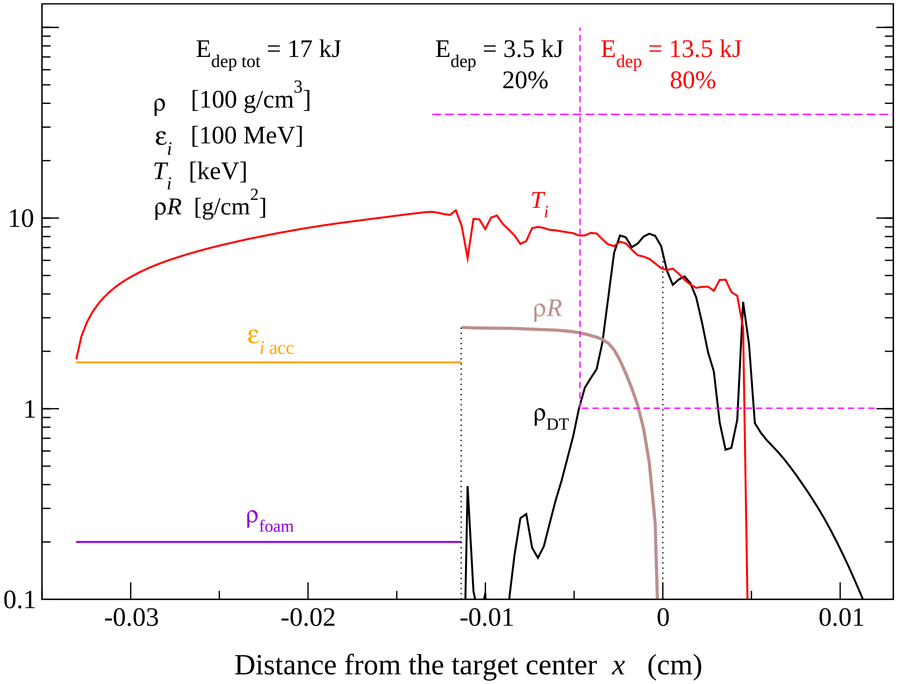
$$A_{\mathrm{ig}} = \frac{\eta F_{\mathrm{hs}} \pi r_{\mathrm{ig}}^2}{P_{\mathrm{las}} \tau_{\mathrm{las}}} \approx 17\%\ \ (\eta = 0.8)$$

Reduced laser intensity

Scenario with lower laser intensity

$$I_{\rm las} = 5\times10^{21}\ {\rm W/cm^2}\ (a_0 \approx 35) \longrightarrow \varepsilon_i = 175\,{\rm MeV}$$

Profiles after ion stopping:
(*Trumpet code*)



Design with same $D,\ l_{\rm acc},\ \delta\theta$ as before:

With $r_{\rm acc} \approx 10\,\mu{\rm m}$: $F_{\rm acc} = 5.6\,{\rm GJ/cm^2}$

$$F_{\rm hs} = 1.9\,{\rm GJ/cm^2}$$

$$E_{\rm hs:ig} = 8.4\,{\rm kJ}$$

ignition

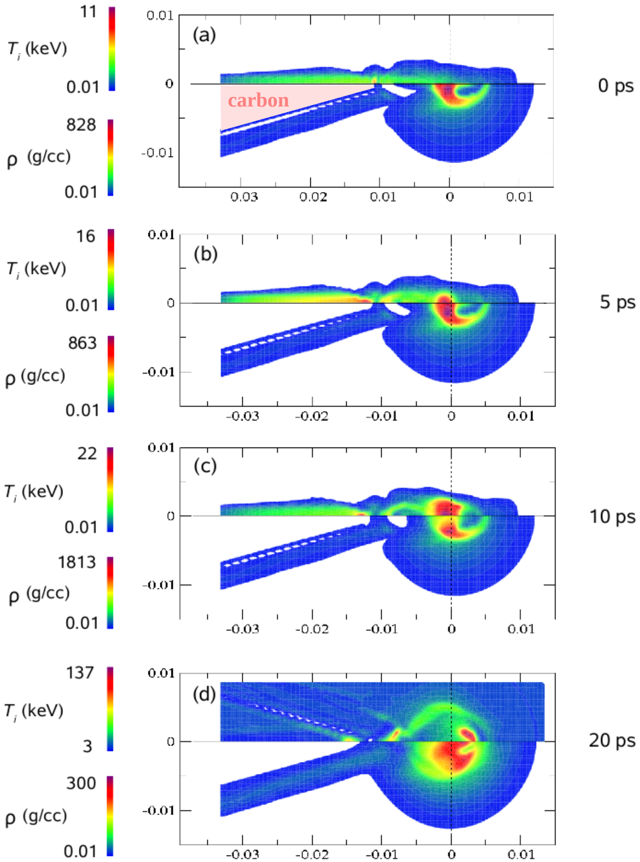
$$P_{\rm las} = 15\,{\rm PW},\quad \tau_{\rm las} = 7\,{\rm ps}$$

$$E_{\rm las} = 100\,{\rm kJ}$$

$$A_{\rm acc} \approx 17\,\%$$

DT target dynamics

2D axially-symmetric CHIC simulation after ion beam energy deposition



Further heating after ion beam energy deposition by α - particles

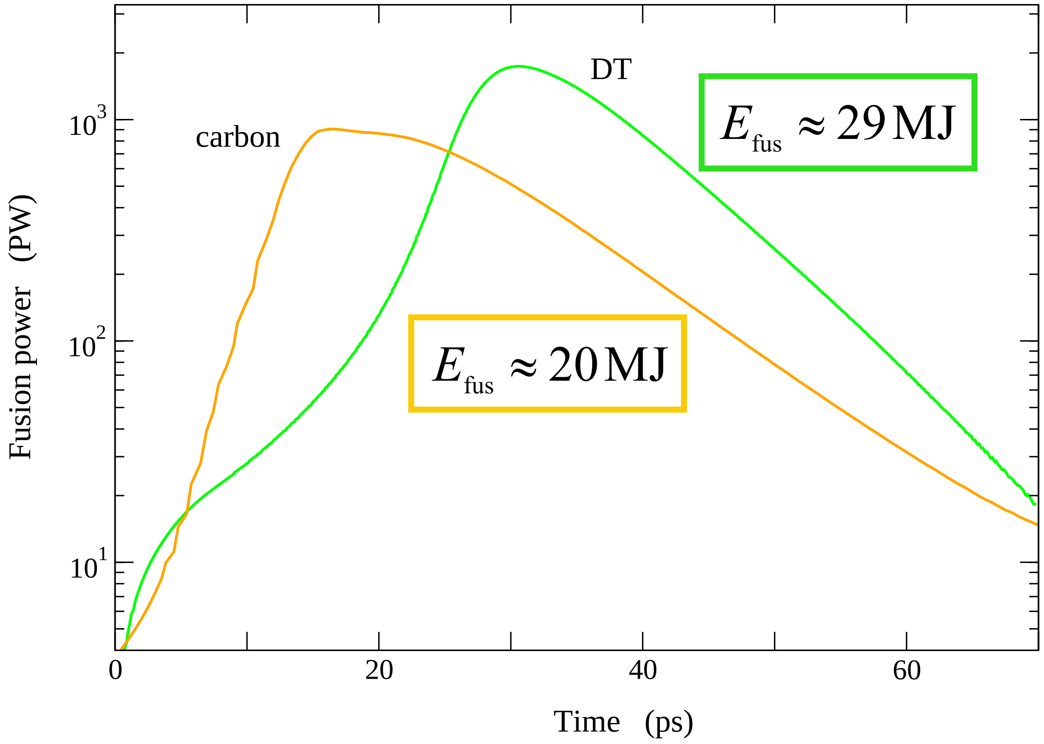
reaction rate: $\nu_{\mathrm{DT}} \approx 2.6\times10^5 \rho T_i^2 \,\mathrm{s}^{-1}$

equilibration time: $\tau_{\alpha e} \approx \beta \dfrac{T_e^{3/2}}{\rho}\,\mathrm{ps}$

← ignition

← combustion

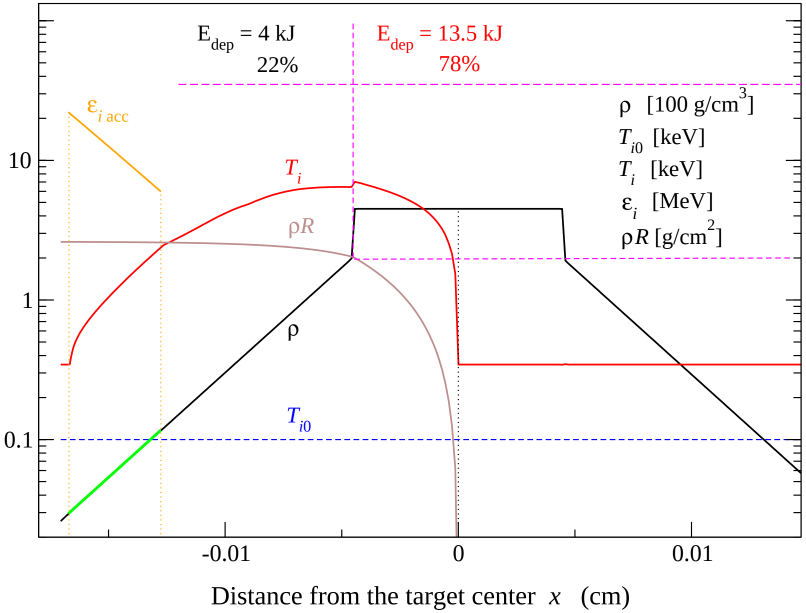
Fusion power and energy



In-situ DT acceleration

Large-scale target: $(\rho R)_{\text{core}} \approx 2.6\,\text{g/cm}^2,\ \rho_{\max} \approx 450\,\text{g/cm}^3$

Profiles after ion stopping:
(*Trumpet code*)



Ignition scaling laws:

$$E_{\text{ig}} = 8.5\,\text{kJ},\ r_{\text{ig}} = 13.5\,\mu\text{m},\ \tau_{\text{ig}} = 15\,\text{ps}$$

DT acceleration: $\langle \varepsilon_i \rangle \approx 10\,\text{MeV}$

$$I_{\text{las}} = 4.6\times10^{22}\ \text{W/cm}^2,\ r_{\text{acc}} = 7\,\mu\text{m}$$

$$l_{\text{acc}} = 40\,\mu\text{m},\ D = 80\,\mu\text{m}$$

$$N_i \approx 6\times10^{21}\ \text{cm}^{-2},\ F_{\text{acc}} \approx 11\,\text{GJ/cm}^2$$

Beam divergence: $\delta\theta = 0.1$

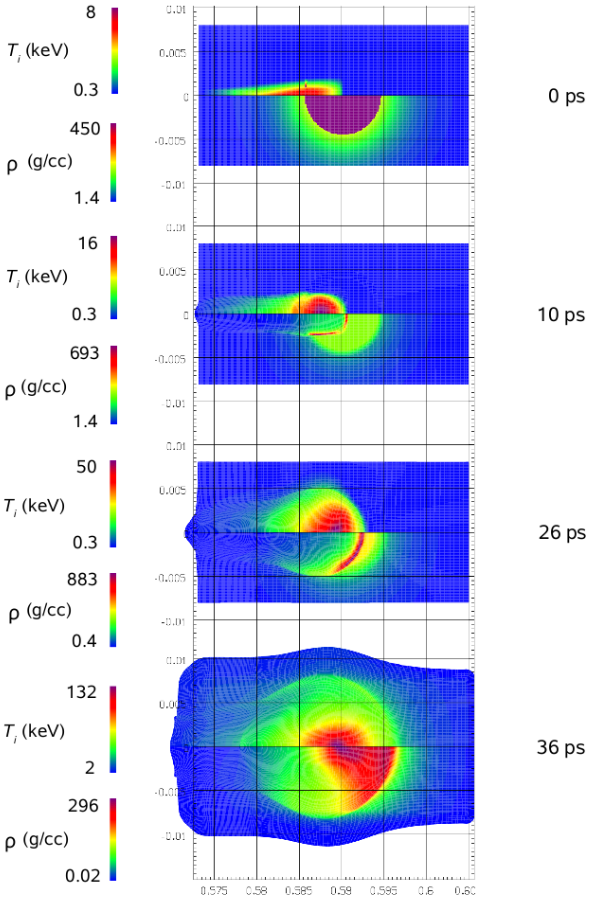
$$\longrightarrow\ F_{\text{hs:ig}} = 1.9\,\text{GJ/cm}^2$$

$$E_{\text{hs:ig}} = 9\,\text{kJ}\ \ (\eta = 0.2)$$

Ignition requirements: $P_{\text{las}} = 70\,\text{PW},\ \tau_{\text{las}} = 2.5\,\text{ps},\ E_{\text{las}} = 180\,\text{kJ},\ A_{\text{acc}} \approx 9\%$

DT target dynamics

2D axially-symmetric CHIC simulation after ion beam energy deposition



ignition

combustion wave

Conclusions

High-energy carbon ions

- **high acceleration efficiency** ← ***lower plasma density***
- **enhanced localization of ion energy deposition**
- **low ion beam divergence** ← ***high ion energy***
- **reduced demand of laser energy for DT ignition**
- **ion beam divergence?**
- **cone**

In-situ DT acceleration

- **simple geometry**
- **but: lower acceleration efficiency**
  - **larger ion beam divergence**
  - **hole-boring through undercritical plasma**
  - → **higher laser power and energy**