Petawatt-class laser accelerated high energy mid-Z ions for nuclear physics

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Outline

- Introduction
- Ionization problem
- Acceleration problem
  - Acceleration by the ponderomotively shifted electrons
  - Optimal conditions
  - Longer pulses
  - Shutter technology
- Conclusions

Introduction

- Laser techologies
  - Power >1PW
  - Intensity $>10^{22}$ W/cm^2
- Ion acceleration
  - TNSA, RPA, BOA, DCE
  - Applications
    - Inertial confinement fusion
    - Imaging
    - Cancer treatment
    - Particle colliders
  - Protons and light ions are mostly under consideration
- Mid-Z ions
  - Nuclear physics
  - HED physics
  - Ionization rate?
  - Lower charge-to-mass ratio

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Ionization problem

- Experiment and theory shows that highly charged ions can be produced effectively
- Using the Keldysh formula it can be shown that ions with Z < 21 are fully ionized
- We have used the Popov-Perelomov-Terentiev model to estimate a tunnel ionization rate

$$w_Z(|\vec{E}|)=\omega_a \kappa^2 \frac{(2l+1)(l+m)!}{2^{mm}!(l-m)!} C_{\kappa l}^2 2^{2\hat{n}-m} F^{m+1-2\hat{n}} \exp\left(\frac{-2}{3F}\right)$$

$$C_{\kappa l}^2=\frac{2^{2\hat{n}-2}}{\hat{n}(\hat{n}+l)!(\hat{n}-l-1)!}$$

$$F=\frac{|\vec{E}|}{\kappa^3} E_a \qquad \kappa=\sqrt{\frac{I_Z}{I_H}} \qquad n^e=\frac{Z}{\kappa}$$

$$\omega_a=\frac{m e^2}{h^3}=4.13\times 10^{16}\ s^{-1} \qquad E_a=\frac{m^2 e^5}{h^4}=5.1\times 10^9\ \frac{V}{cm}$$

- We chose Fe-ions as an example

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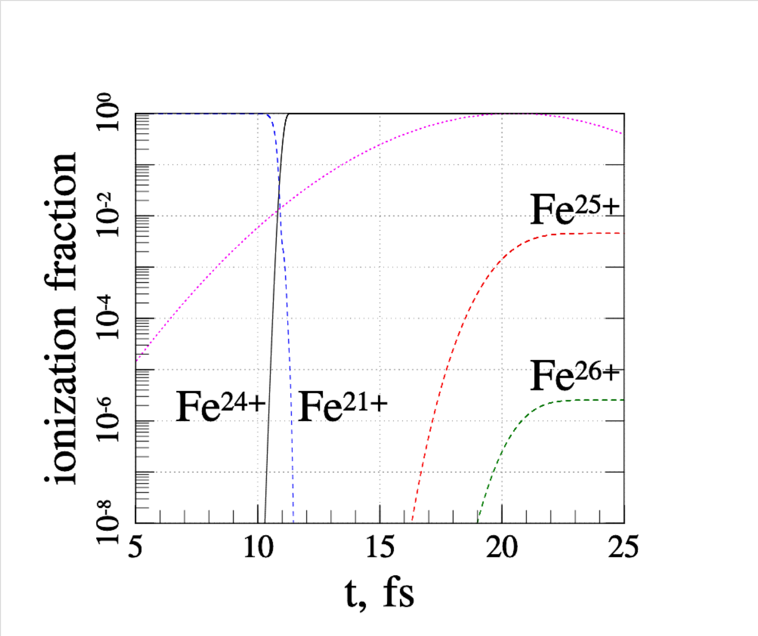
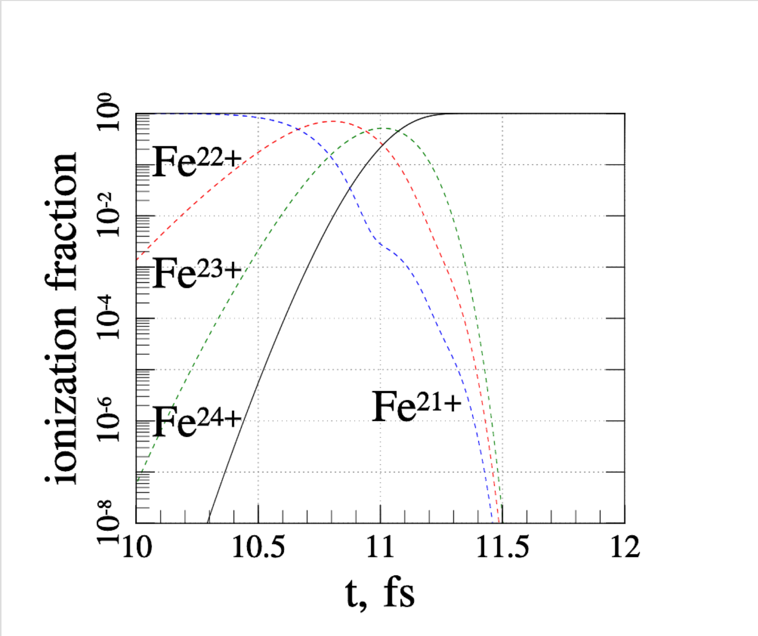
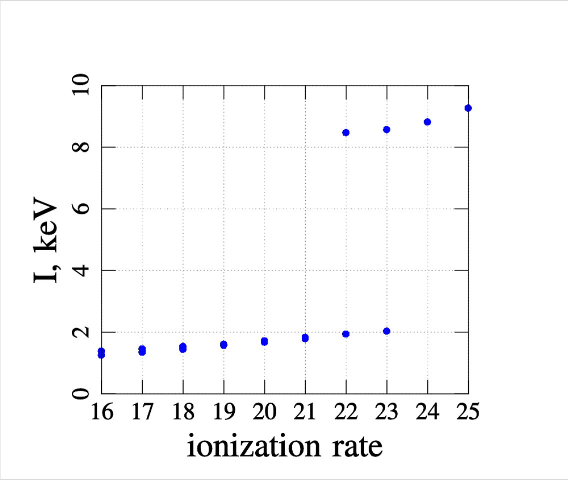
Ionization problem





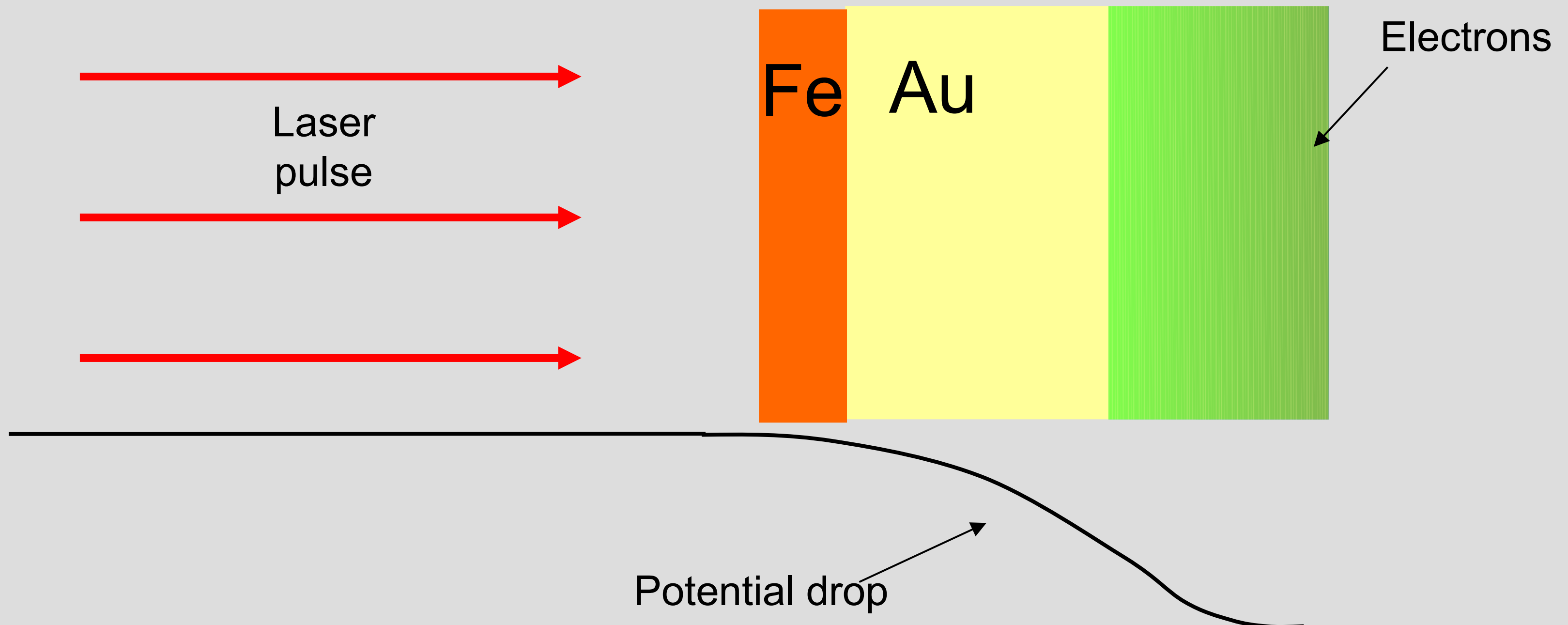


JETP Lett. 86, 577 (2008)

Acceleration problem

- TNSA
- RPA (Light sail, Piston,..)
- BOA (Yin et al., Phys. Plasmas, 2007)
- Direct Coulomb Explosion (Bulanov et al., PRE, 2008)
- Acceleration by Ponderomotively Shifted Electrons (Korzhimanov et al., JETP Lett., 2007)

- Ions should \`feel\` the highest field
  - TNSA and RPA are hardly suitable
- Low charge-to-mass ratio
  - H+: 1
  - C6+: 0.5
  - Fe24+: 0.43
  - Au68+: 0.35



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Acceleration problem
Theory

$$n_0 = \frac{N_{e0}}{N_{cr}} \qquad N_{cr} = \frac{m\omega^2}{4\pi e^2} \qquad \zeta = \frac{\omega z}{c}$$

$$I = \frac{4\pi e^2}{m^2 \omega^2 c^3} I[W/cm^2] =$$

$$= 2.75\times10^{18} \lambda^{-2}[\mu m]\, I[W/cm^2]$$

- For bound electrons:
  $$f_{pond} = f_{el} = n_0 \zeta_b$$
- In the case of total reflection:
  $$f_{pond} = 2\sqrt{I}$$
- So the boundary position:
  $$\zeta_b = \frac{2\sqrt{I}}{n_0}$$
- And potential drop:
  $$\Delta\varphi \approx \frac{n_0 \zeta_b}{2} \approx \frac{2I}{n_0}$$
- Optimal concentration is defined by the relativistic transparency threshold (Cattani et al, PRE, 2000):
  $$n_0^{cr} \approx \sqrt[4]{\frac{64 I}{27}}$$
- Ion energy in optimal regime:
  $$\varepsilon_i \approx 1.3 Z I^{3/4} mc^2$$
- It gives 110 MeV/u Fe24+ ions for 10^{22} W/cm^2 laser pulse at λ = 800 nm

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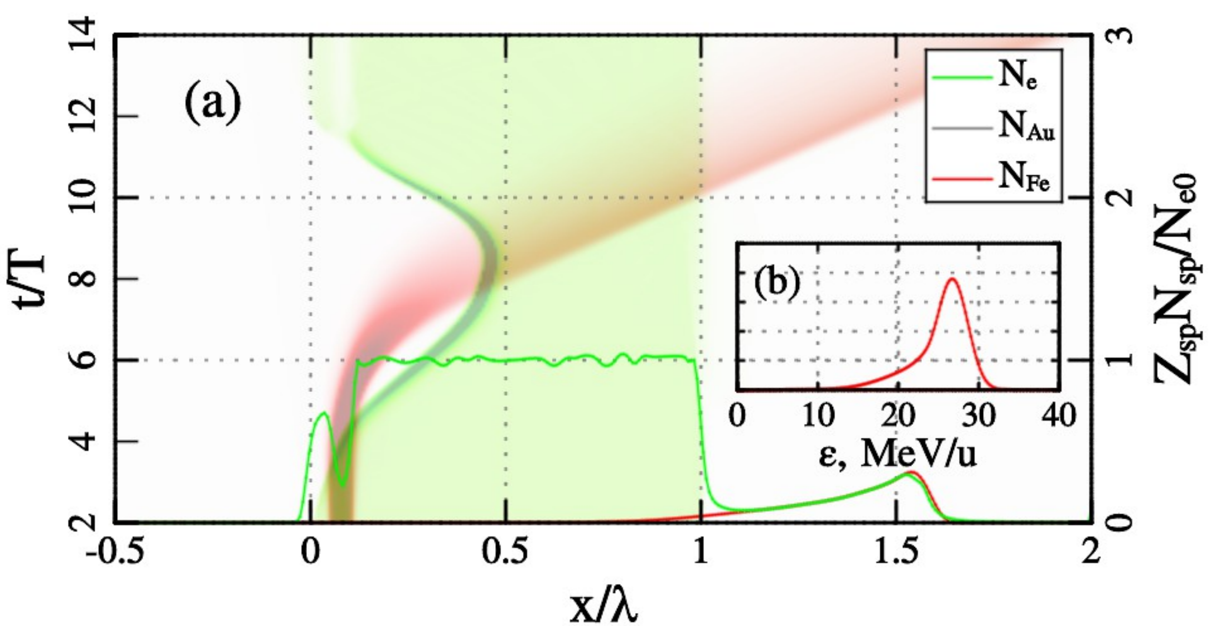
Acceleration problem
1D simulations

$$800\,nm\,Au_{197}^{68+} \quad N_{Au}=5\times10^{20}\,cm^{-3}(n_0=30)$$
$$40\,nm\,Fe_{56}^{24+} \quad N_{Fe}=2\times10^{21}\,cm^{-3}(n_0=60)$$
$$10^{22}\,W/cm^2\,15\,fs\,@\,800\,nm$$



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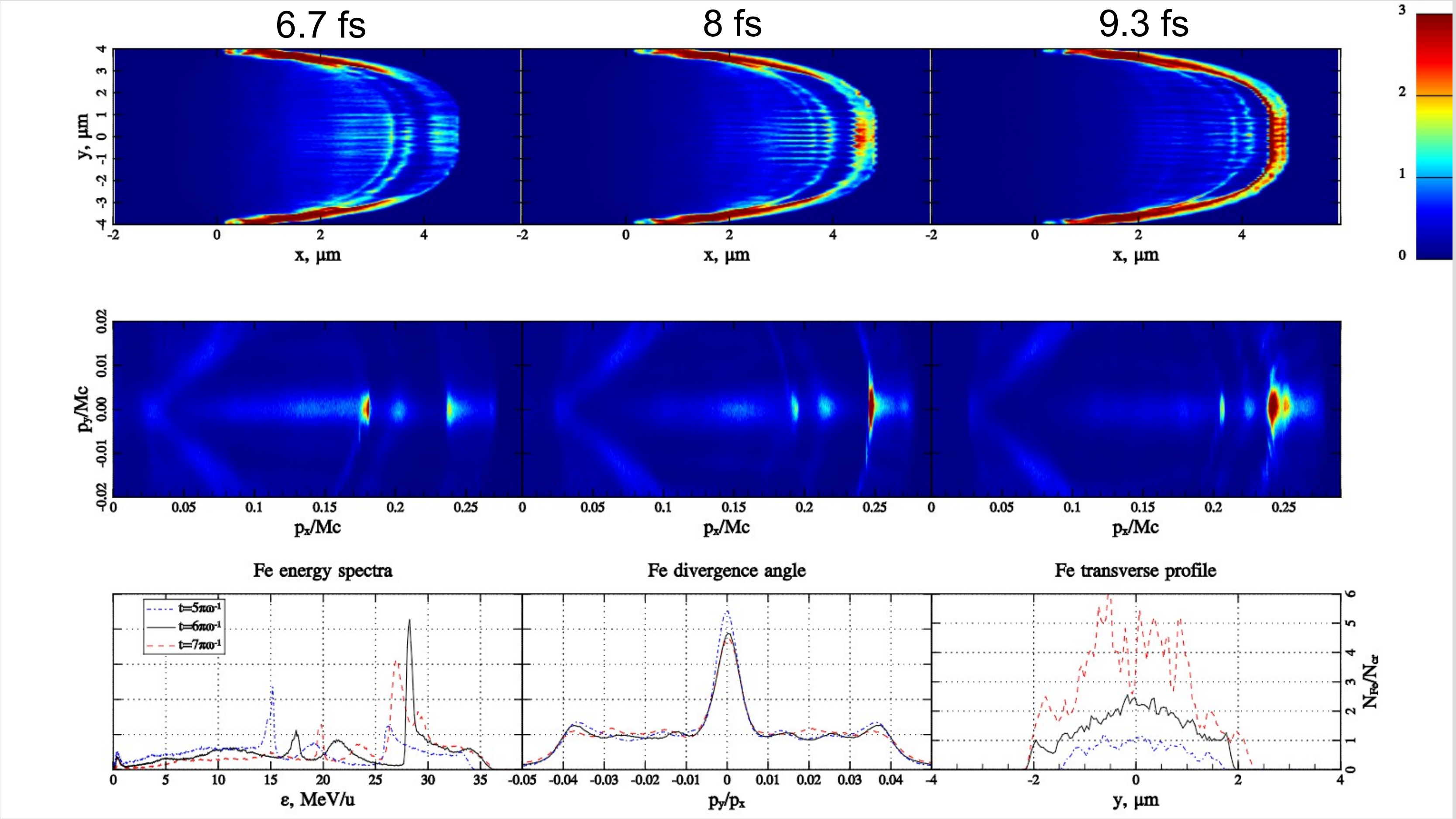
Acceleration problem
2D simulations

Instabilties become the main limiting factor



ELMIS PIC code (http://www.ipfran.ru/english/structure/lab334/simlight.html)

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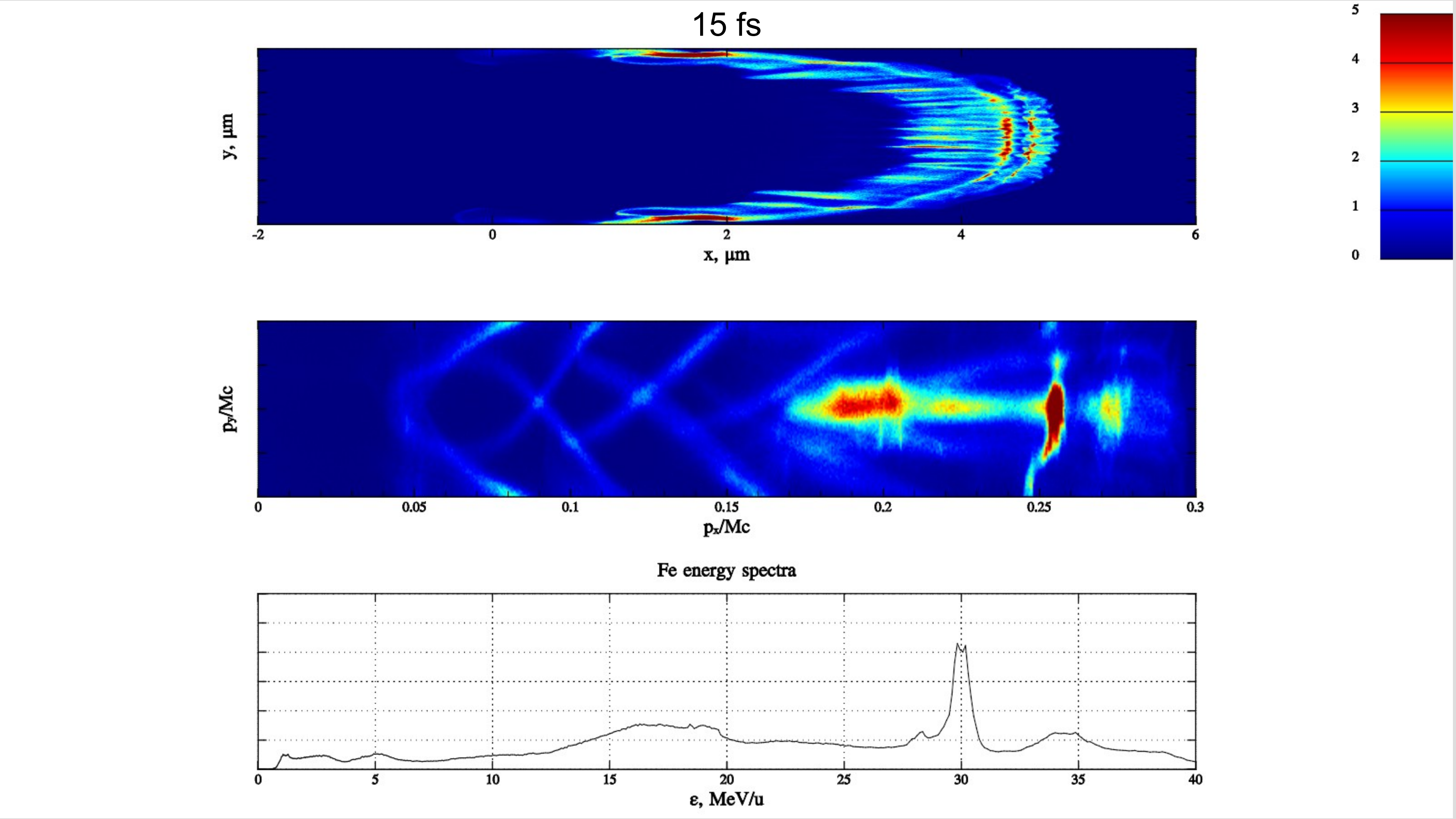
Acceleration problem
Longer pulses



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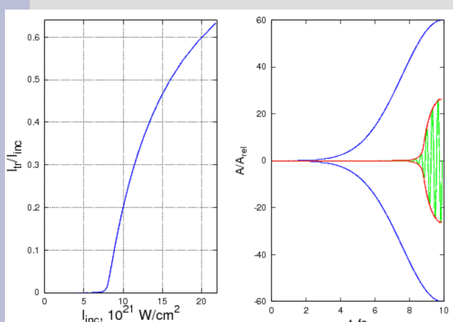
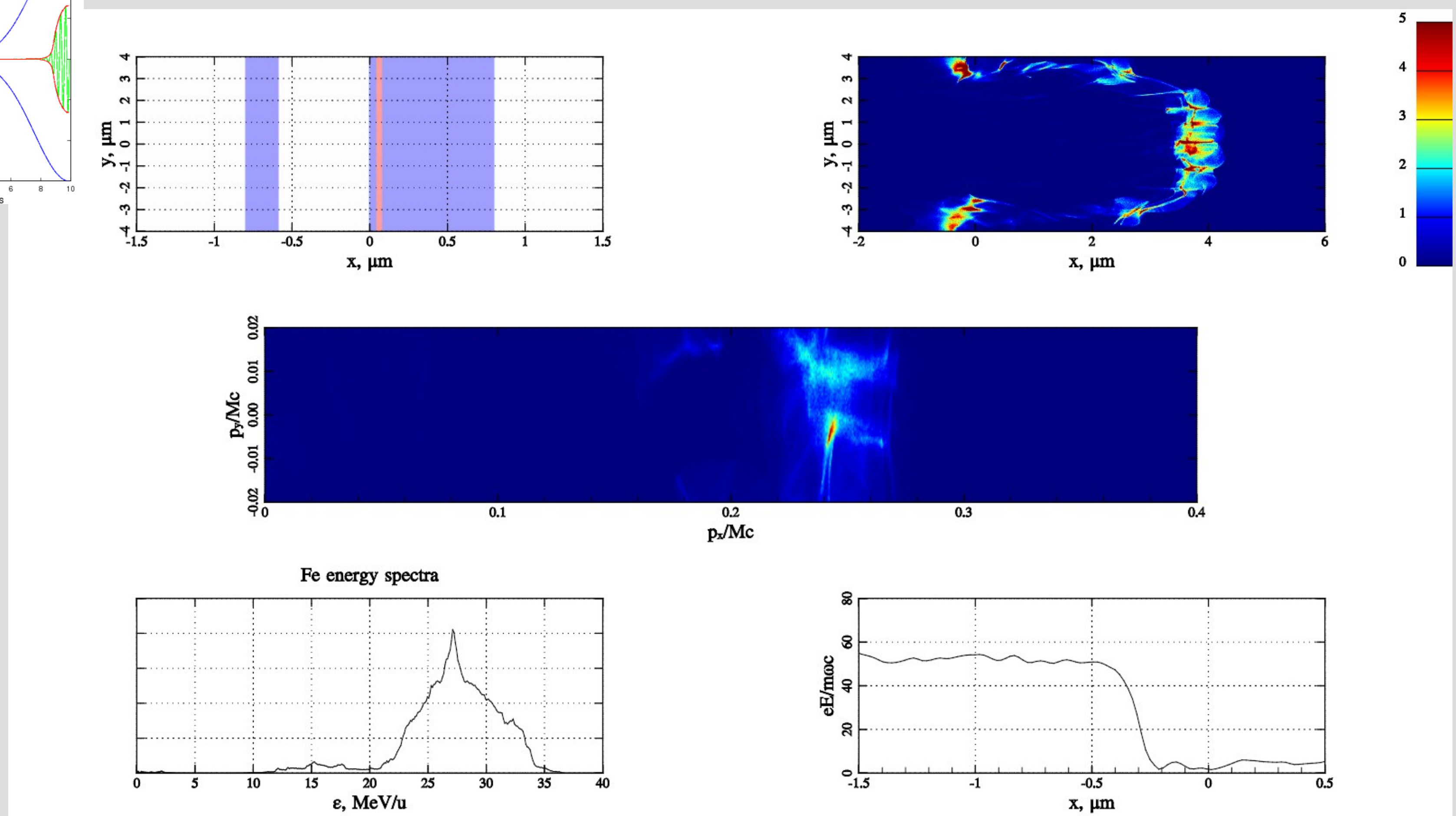
Acceleration problem
Shutter

Shutter is a $270\,nm$ $10^{21}\,cm^{-3}$ Au foil placed in front of main target





Acceleration problem
Ion bunch characteristics

- Total number of ions: 1.8×10^{9}
- Total charge: $7\ nC$
- Beam duration: $5\ fs$
- Ion current: $1.4\ MA$
- Total energy: $0.5\ J$
- Ion beam power: $80\ TW$

Conclusions

- A new method of mid-Z ion acceleration from compound foils by circular polarized laser pulses is proposed
- Heavy ions with Z ~ 20—30 may be produced and accelerated up to energies of tens of MeV/u with current femtosecond laser systems
- Output ion beams may have energy spread as low as 2% and provide ion currents of hundreds of kA; ion beam power is as high as several tens of TW
- Such ion bunches may be used in experimental nuclear physics as an alternative of low-current bunches from conventional accelerators

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