On the possibility of a laser assisted nuclear fusion in micron-scale ^{14}N clusters

Yuji Fukuda[1], K. M. Spohr[2,3], C. -J. Yang[2]

1 *Kansai Institute for Photon Science (KPSI), QST, Japan*
2 *ELI-NP, "Horia Hulubei" National Institute for Physics and Nuclear Engineering, Romania*
3 *School of Computing, Engineering and Physical Sciences, University of the West of Scotland, Scotland*

NEW OPPORTUNITIES AND CHALLENGES IN NUCLEAR PHYSICS WITH HIGH POWER LASERS
ECT*, Trento, Italy
5 July 2024

Contents

1. Introduction

2. A new laser-driven ion acceleration scheme
   in micron-scale H cluster

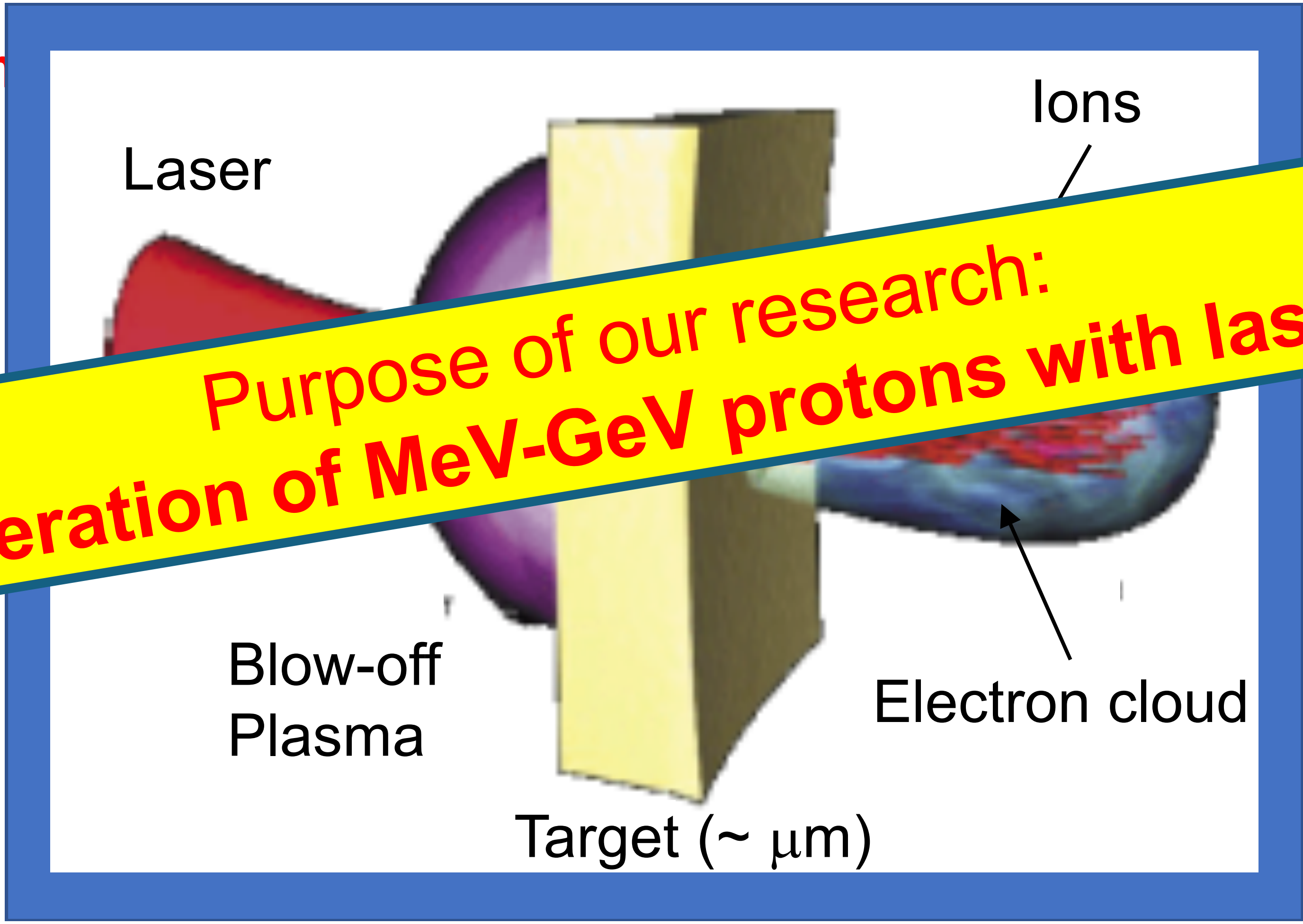
3. Possibility of a laser assisted nuclear fusion
   in micron-scale ^{14}N clusters

Particle Acceleration by Lasers

Particles can be accelerated by huge photon pressure of laser light

when we irradiate the focused laser pulse onto thin Al foil, electrons are push away from the foil, by the huge photon pressure, and ions are accelerated by the electric field created by the electrons.

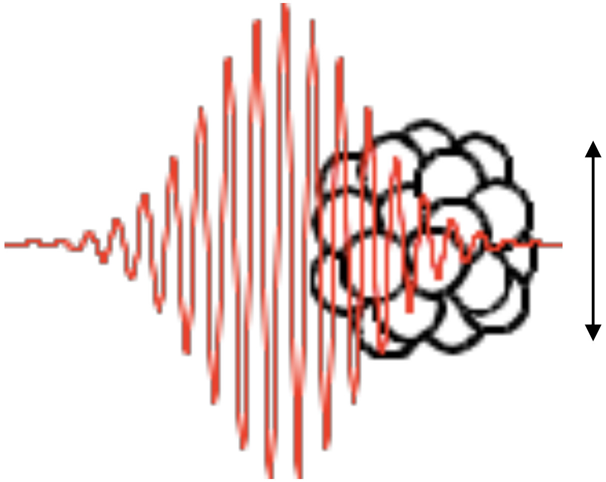
Therm **clear fusion**



Purpose of our research:

Generation of MeV-GeV protons with lasers

Laser-cluster interactions

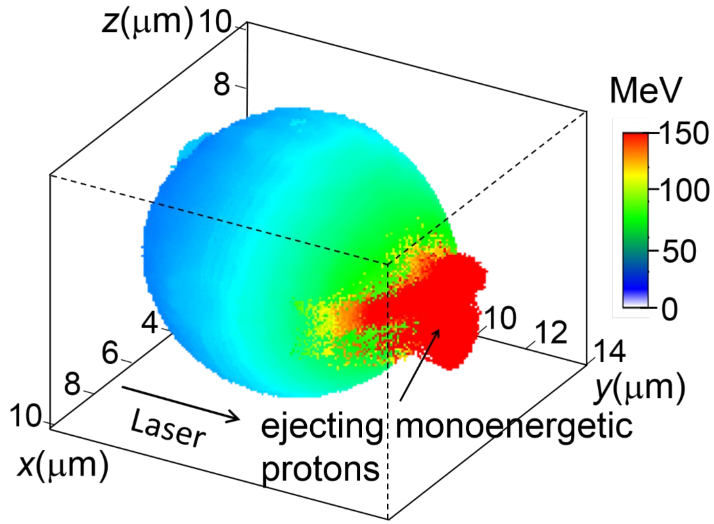


nano-scale

micron-scale

Coulomb explosion of clusters

Shock acceleration “in” clusters



Matsui, Fukuda et al., PRL (2019).

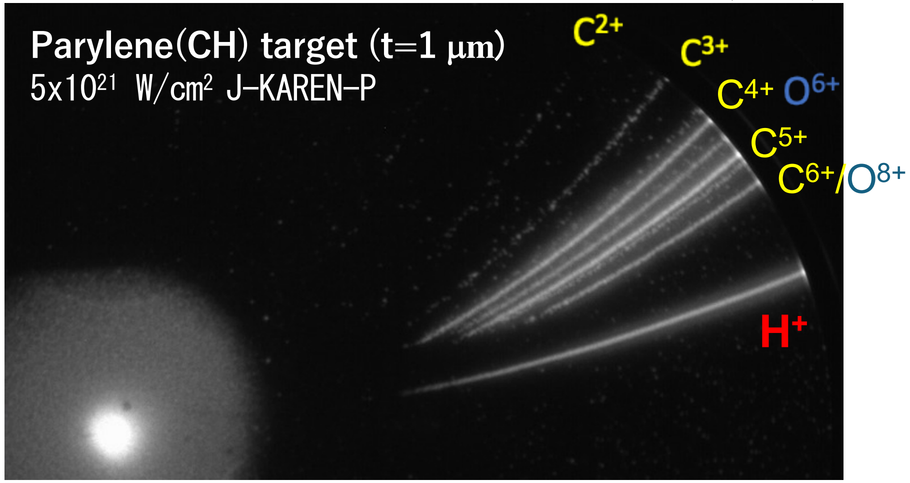
Why - Ion Acceleration with H Clusters?

QST

- In all TNSA type experiments, not only protons, but also high-z ions are accelerated…
- The number of such high-z ions are larger than that of protons…

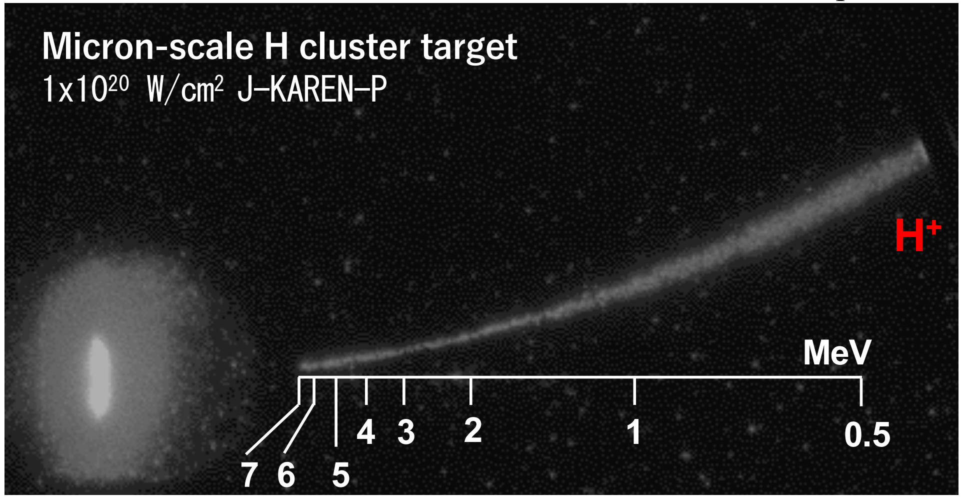
Thin foil targets

Sakawa, Fukuda et al., (2019).



H cluster targets

Jinno, Fukuda et al., Sci. Rep. 2022.



- **Super impurity-free proton beam**
- **High repetition rate (potentially >100 Hz)**
- **Very small amount of debris**
- **Very small amount of x rays (lowest z)**

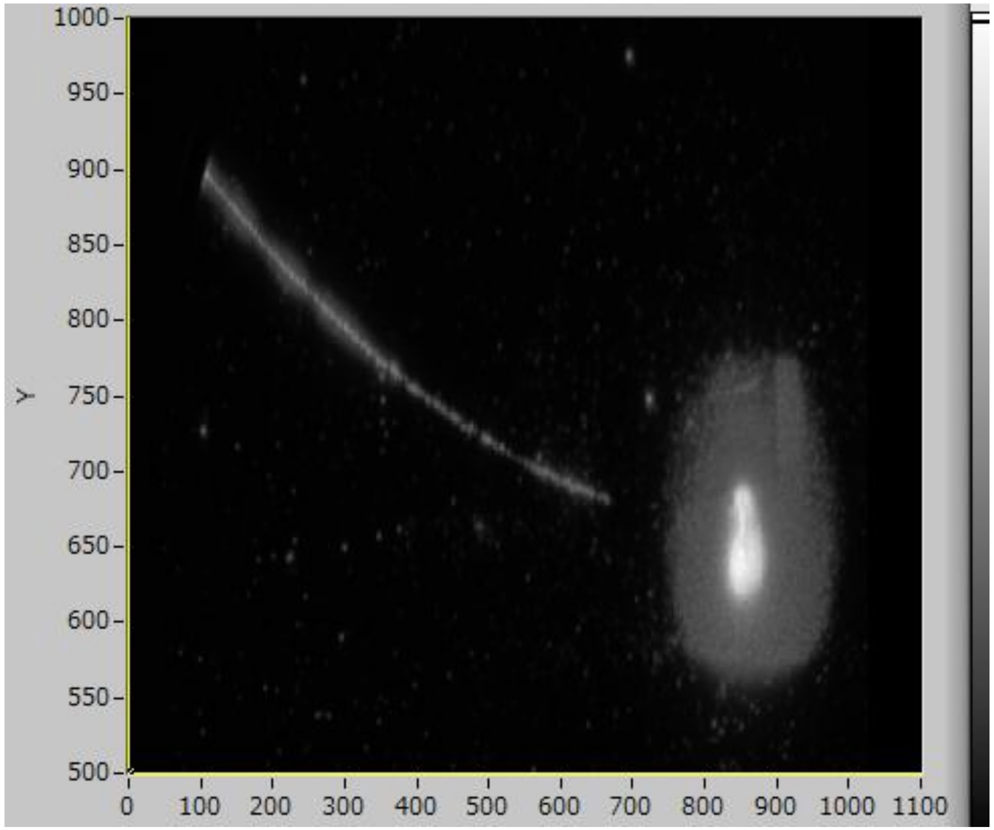
} **Difficult to achieve simultaneously with other types of targets**

➔ Suitable to trigger nuclear reactions

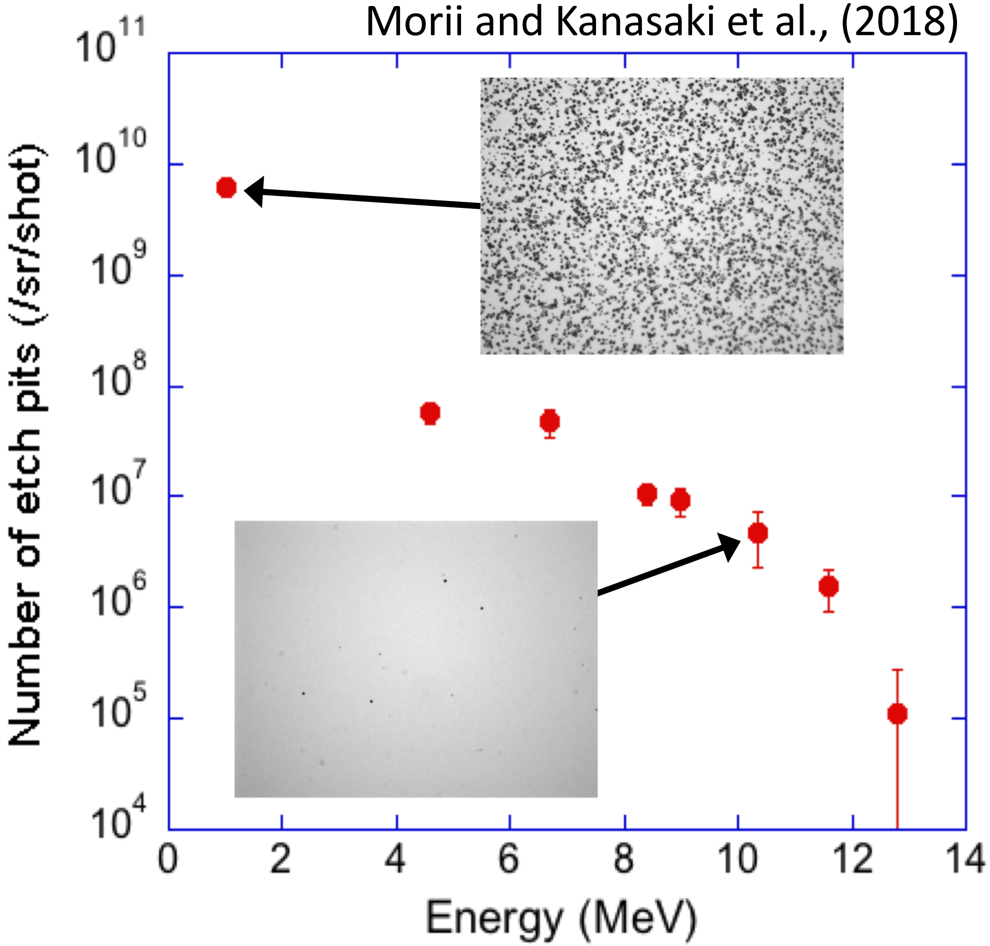
· Other important points:
Solid density hydrogen *(26.8n_c)* ***is suitable to generate*** **Collisionless Shock** : $n_p \sim a_0 n_c$

Multi-MeV Pure Proton Beam Generation at 0.1 Hz

x10 speed



Energy Spectrum: CR-39



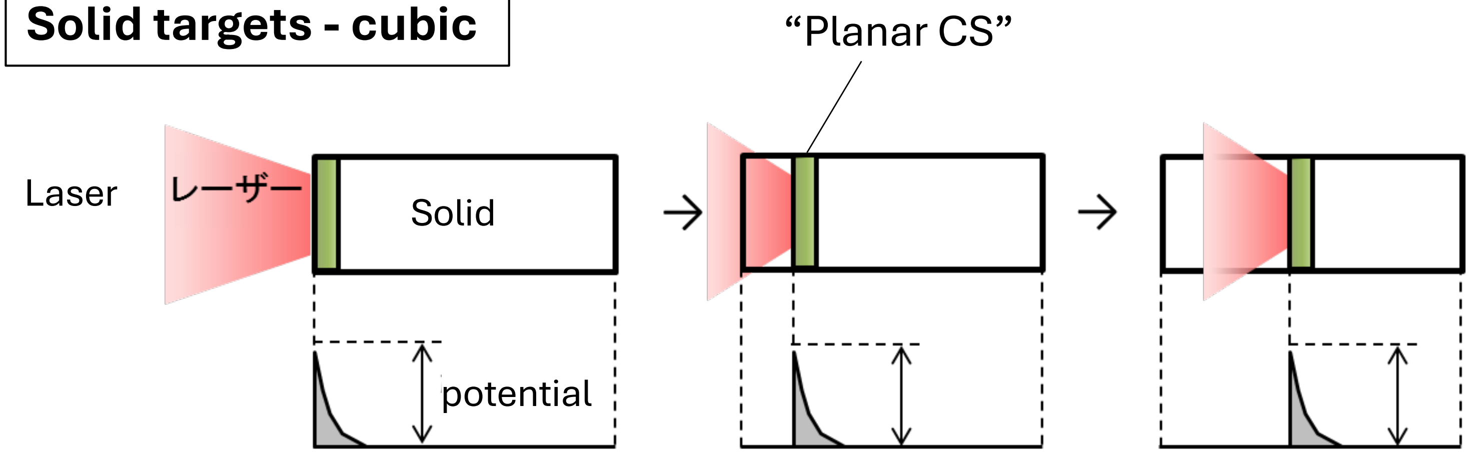
For ~1 MeV range, the number of proton 10^{10}

c.f. micron-scale H cluster contains ~10^{10} H molecules.

For more details, Jinno et al., Sci. Rep. **12**, 16753 (2022).

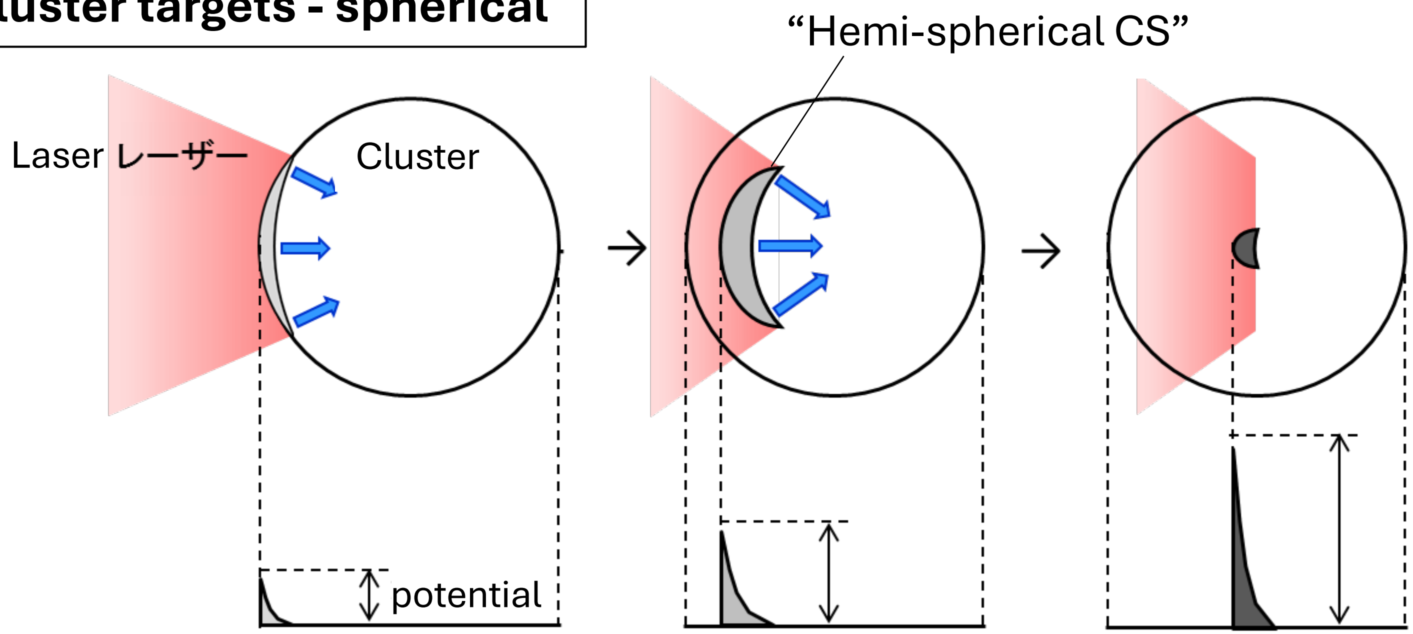
2nd Key Point : Propagation of Collisionless shocks

Solid targets - cubic



- **CS propagates with <u>constant intensity</u> (=potential height)**

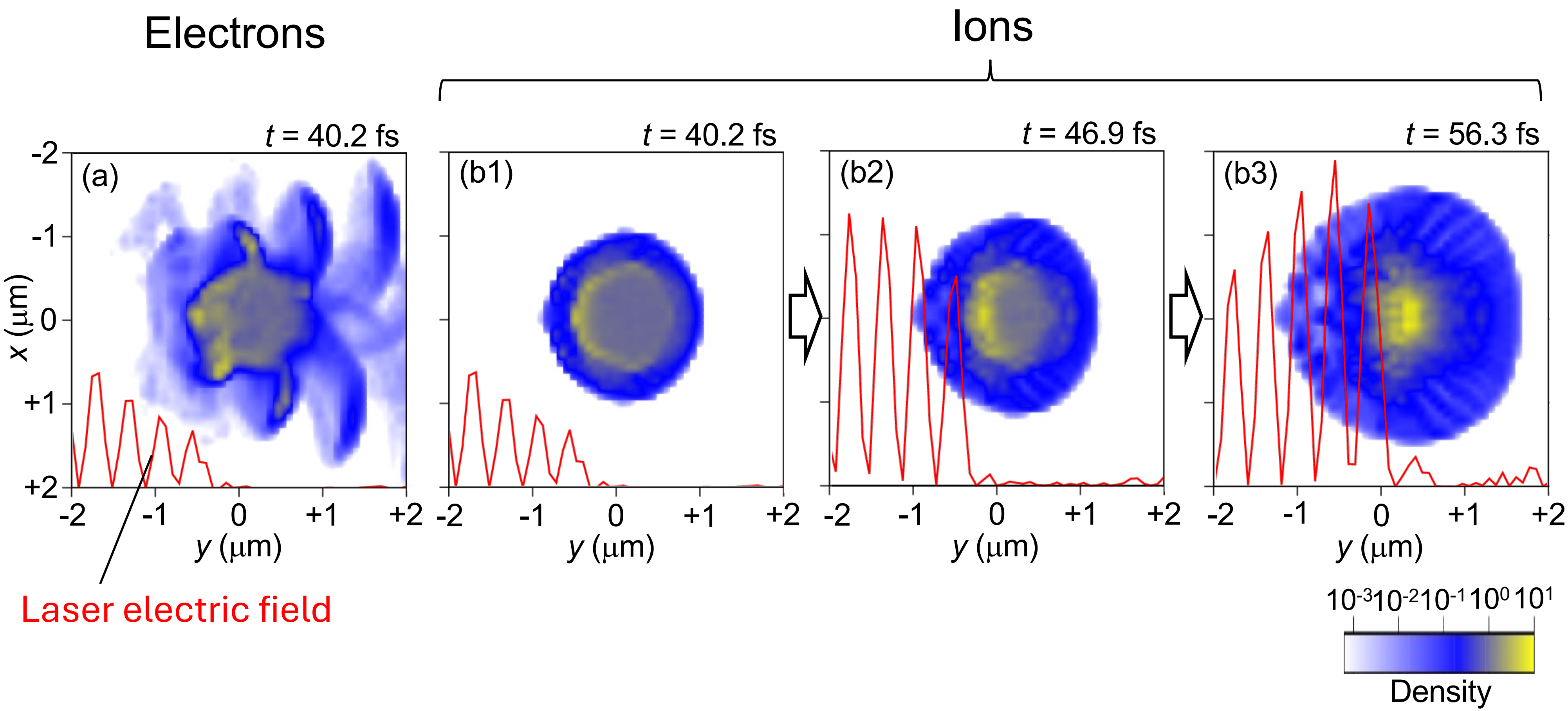
Cluster targets - spherical



- **CS propagates inward and converges with increasing its intensity (=potential h**

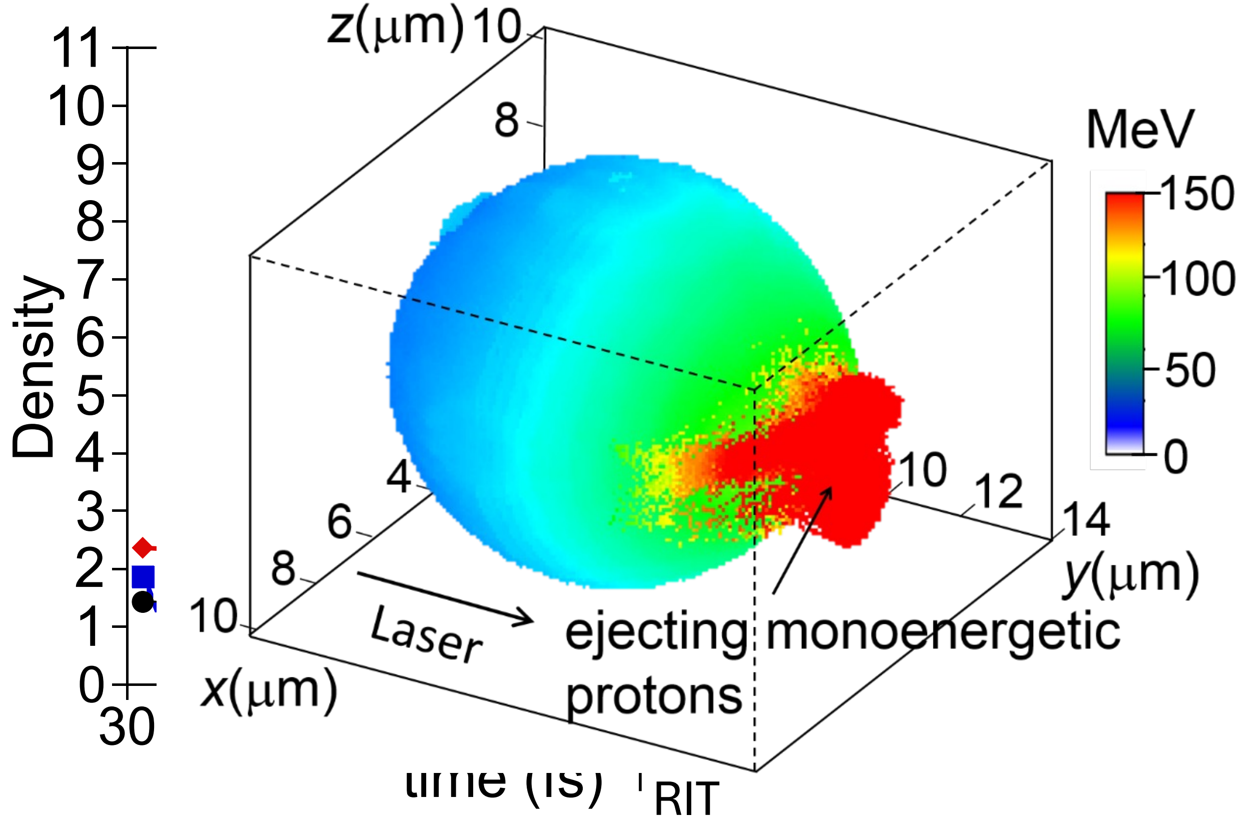
Time History of Electron/Ion Density Distributions

New acceleration scheme:
CSBA (=Converging Shock-induced Blow-off Acceleration)

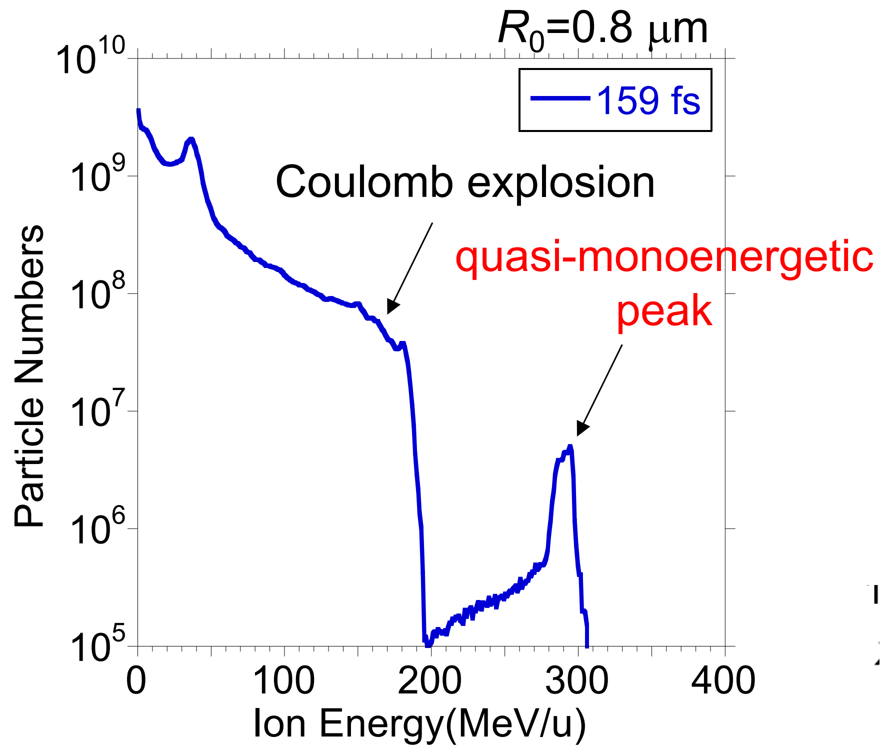


- ✓ **Electrons are strongly pushed forward by PF and pile up to trigger CS**
- ✓ **Outside: Ions expand due to Coulomb explosion**
- ✓ **Inside: CS propagates inward, converges, and pushes (=accelerates) ions**

Detailed Electron/Ion Dynamics inside CS



Proton Energy Spectrum



t < 51 fs : Shock propagates inward while maintaining the crescent shape

t = 51 fs : Ion density sharply increases and exceeds electron density

<u>CSBA starts to operate</u> : shock potential > kinetic energy of upstream protons

t = 56 fs：Laser pulse peak and the converging shock reach the cluster center at the same time.

<u>RIT becomes dominant</u>, simultaneously:

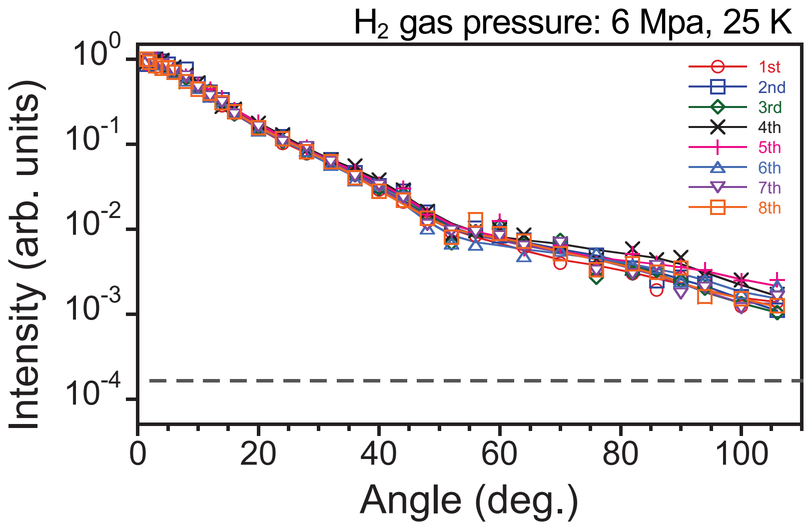
t = 60 fs：End of the CSA : shock structure collapses

※ RIT : Relativistic Induced Transparency

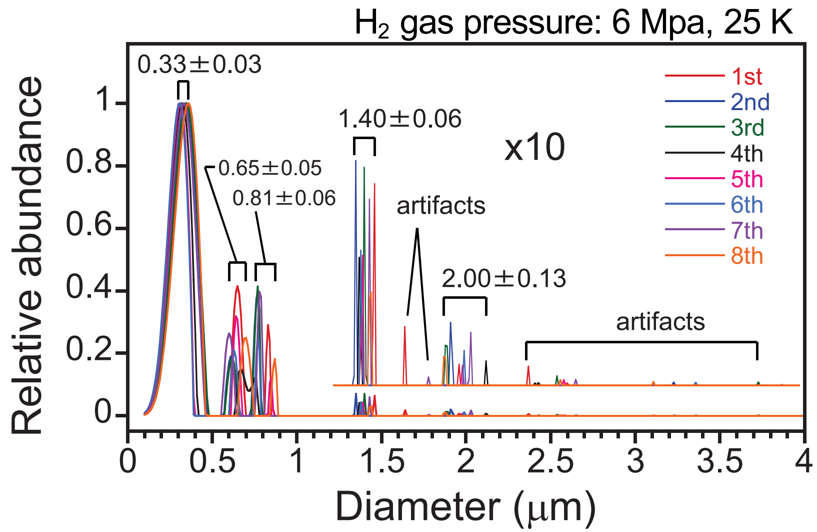
Characterization of Cluster Size using Mie scattering

QST

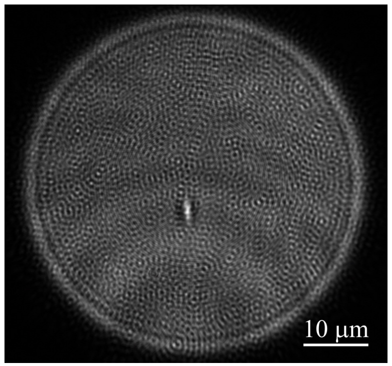
Scattered light intensities



Size distributions for H_2 clusters



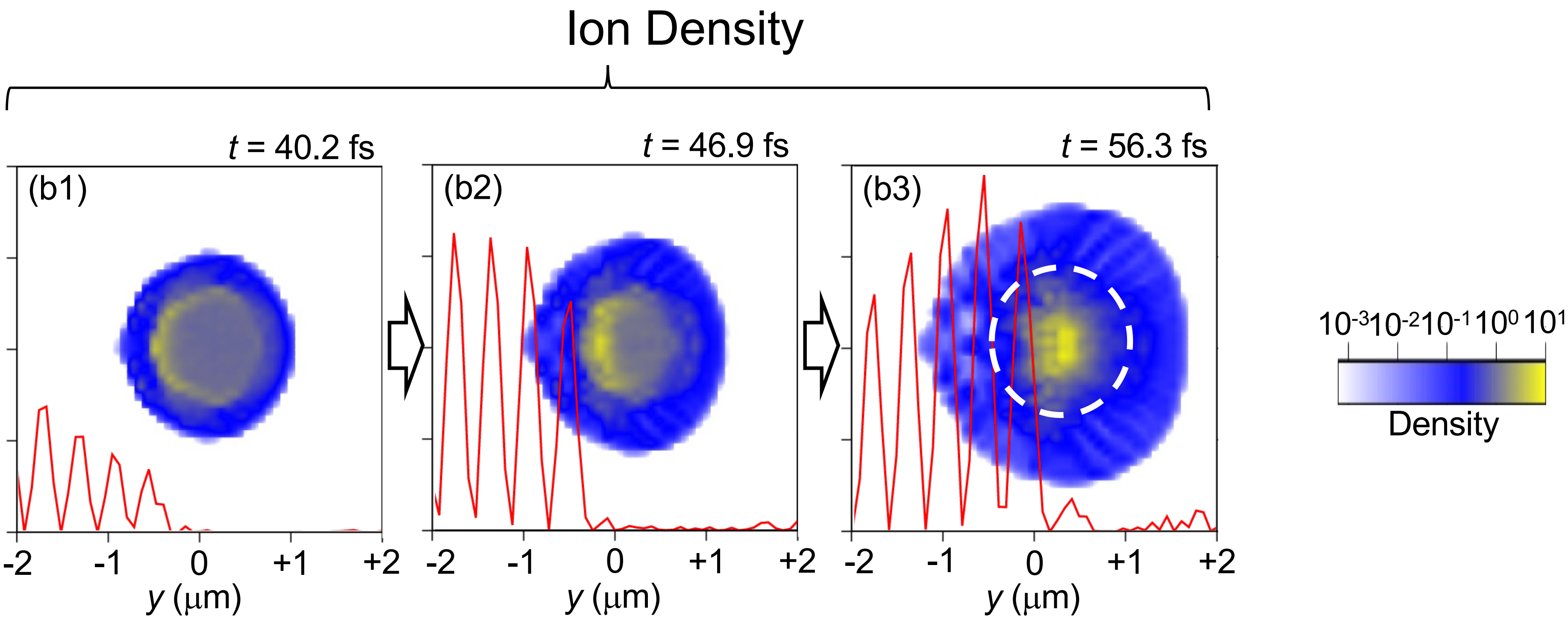
S. Jinno, Y. Fukuda et al., APL**102**, 164103 (2013).
S. Jinno, Y. Fukuda et al., OE**21**, 20656 (2013).
S. Jinno, Y. Fukuda et al., OE**25**, 18774 (2017).
S. Jinno, Y. Fukuda et al., PPCF**60**, 044021 (2018).



Microscope Image
(M.R.=~1700x, F.D.=0.9 um)

Micron-sized H_2 clusters are successfully generated

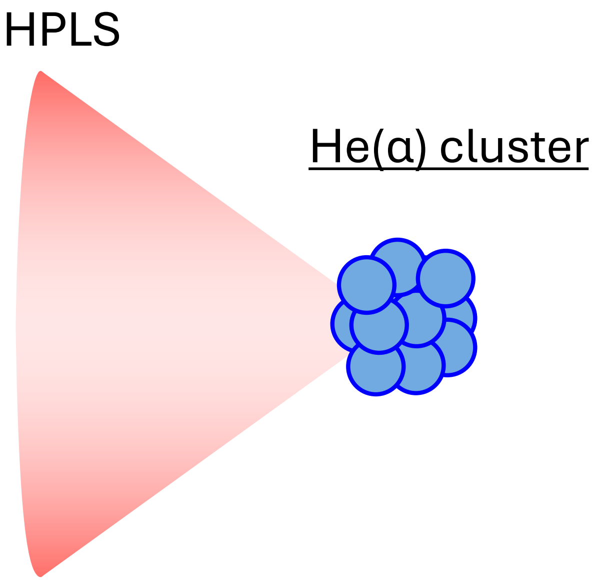
One important outcome

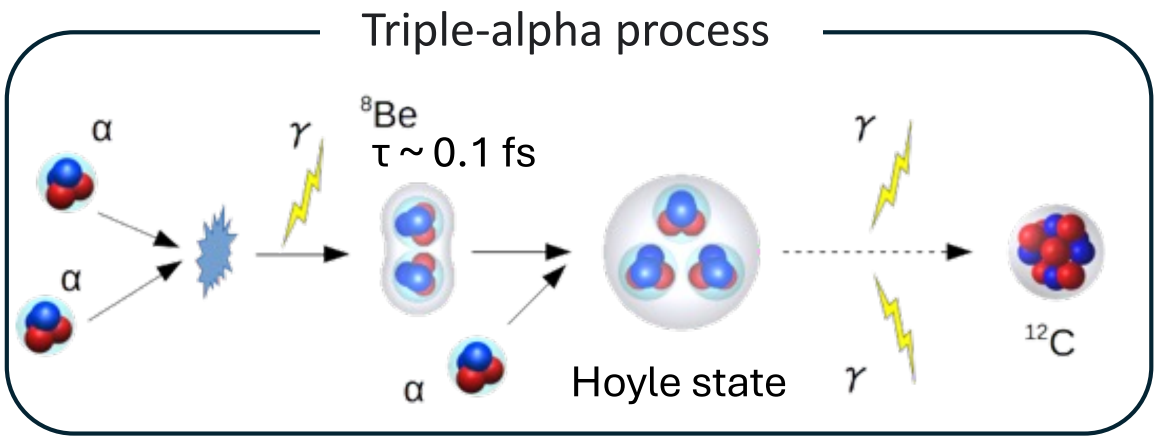


At the central part, <u>ion density increases up to ~10 times</u>
at the peak of laser pulse, lasting for <u>~10 fs</u>

We discuss on the possibility of
a laser assisted nuclear fusion "in" micron-scale clusters

Initial Idea

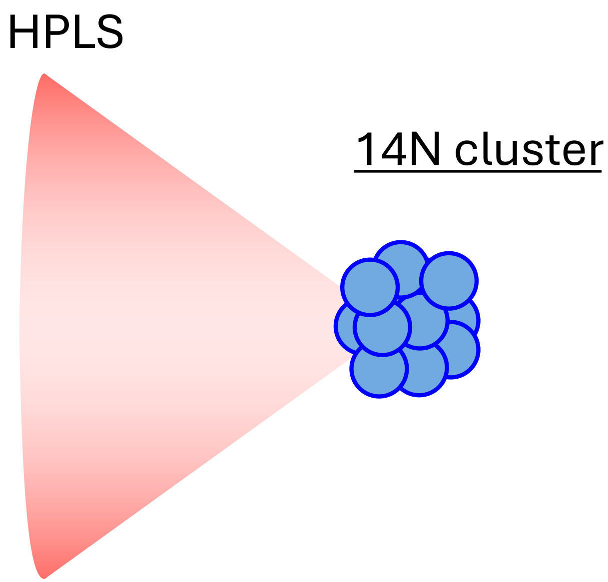




Klaus : Great idea!!

Jerry : unfortunately…it is unrealistic…
because of very short life-time.
It needs very high density environment.

More Realistic System



- **Need to overcome Coulomb barrier $\gtrsim$ 4 MeV (0.3 MeV/u) for 14N**
- **Fusion cross section is significant ($\gtrsim$ 100 mb) for center-of-mass energy Ec.m. $\gtrsim$ 7 MeV (0.5 MeV/u).**

Z. Switkowski et al., Nuclear Physics A 274, 202 (1976).

Q values for 14N +14N

Z. Switkowski et al., Nuclear Physics A 274, 202 (1976).

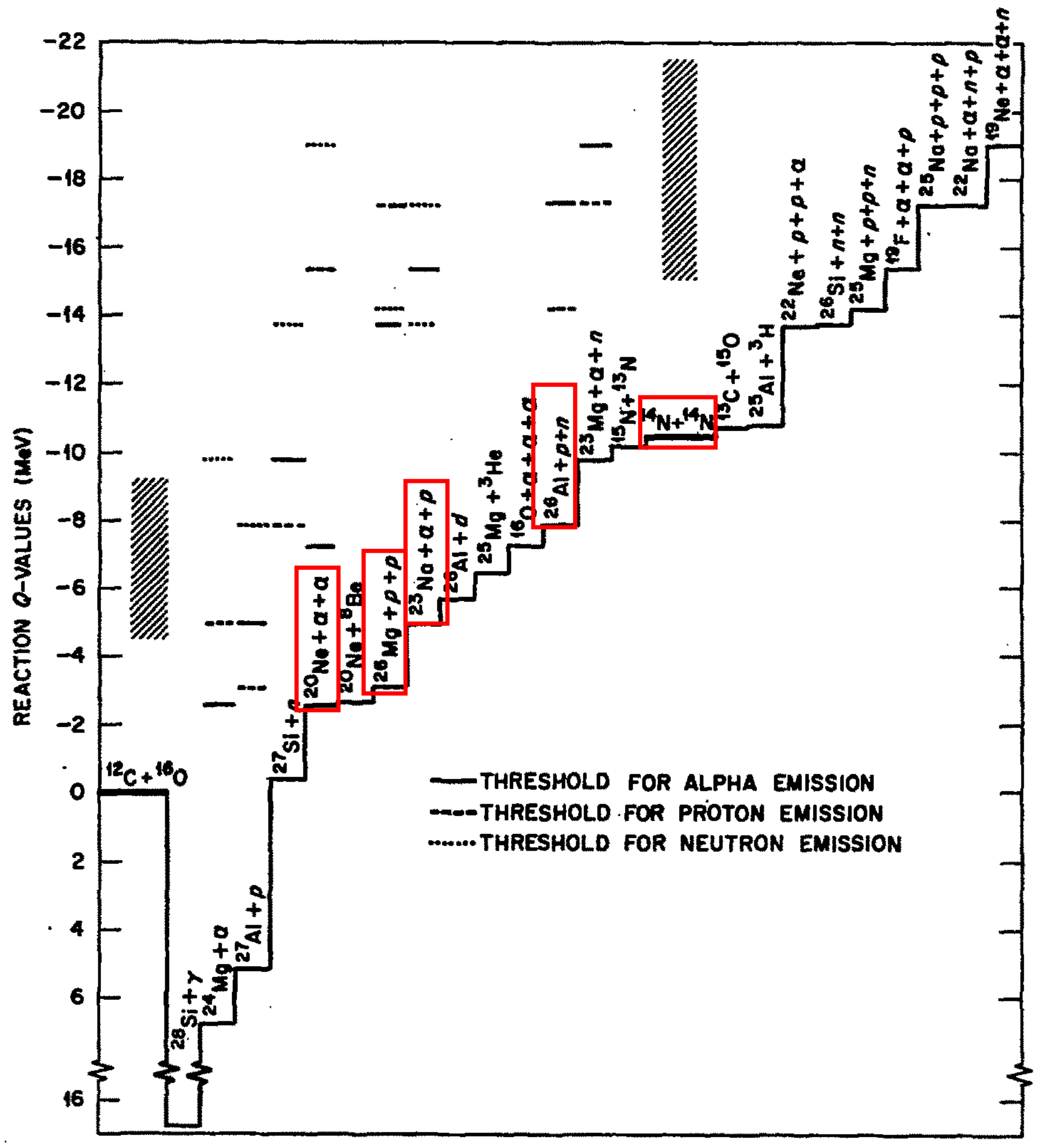


Fig. 1. The Q-values for $^{12}C+^{16}O$ and $^{14}N+^{14}N$ initiated reactions. Ground state Q-values are shown relative to $^{12}C+^{16}O$. For orientation, the energies at which the heavy residual products become energetically unbound to further emission of an α-particle, proton or neutron are indicated by the solid, dashed and dotted lines respectively. The cross-hatched region represents the energies studied in these experiments.

- Expected total fusion events : **10^3-10^4**
  => from one cluster with dia. = 1 um
  (~10^{10} N atoms) @5 × 10^{22} W/cm^2

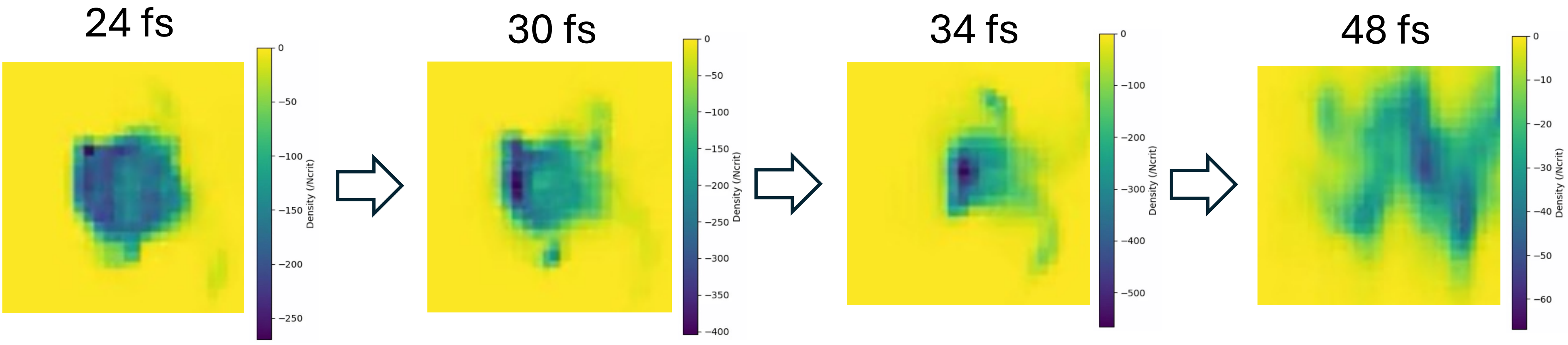
- Expected Fusion reactions:
  => γ ray spectra peaks via Ge(Li) measurements

  ^{14}N + ^{14}N => 20Ne + α + α + 8 MeV
  ^{14}N + ^{14}N => 23Na + p + α + 8 MeV
  ^{14}N + ^{14}N => 26Mg + p + p + 5 MeV
  ^{14}N + ^{14}N => 26Al + p + n + 2 MeV

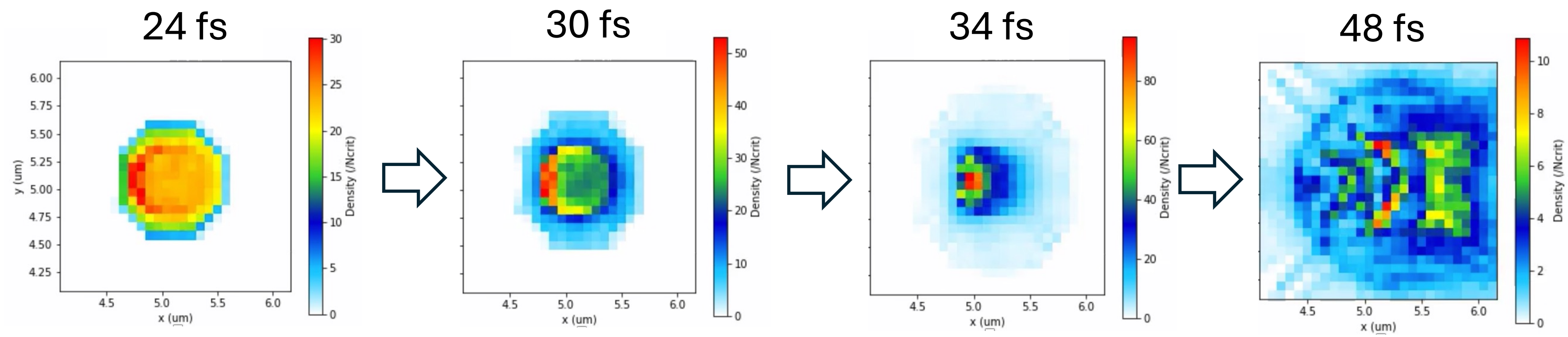
- Estimated Q value : < 0.0001
  => Assuming that each fusion event release 8 MeV energy, carried by proton, neutron, and alpha particles.

Possible advantages of laser-assisted nuclear fusion

Electron density



14N density



- Could be a good test bench for "plasma screening effect"

  => We will have different cross section values, compared to the previous experiment conducted with accelerator, because they used solid targets (nitride titanium).