Cluster-Gas Targets as Efficient Media for Laser-Driven Ion Accelerations

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Outline

1. **Introduction**
   ・Cluster-gas targets

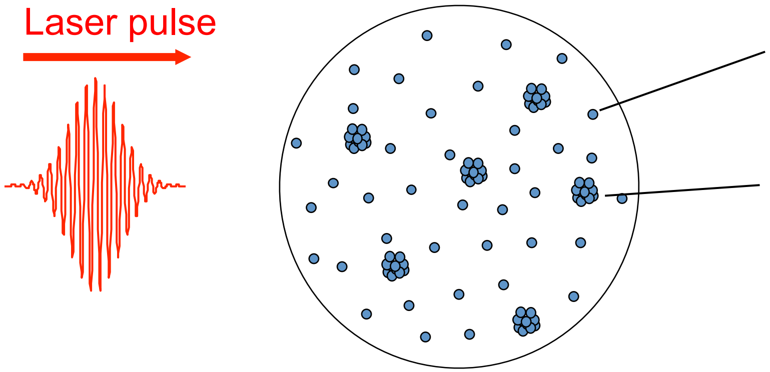
2. **Laser-driven ion acceleration with cluster-gas targets**
   ・The First demonstration using 4 TW TiS Laser
   (40 fs, 150 mJ, 10^{-6} cont.) Fukuda *et al*., PRL **103**, 165002 (2009).
   ・The Second demonstration using 25 TW TiS Laser
   (40 fs, 1 J, 10^{-11} cont.) Fukuda *et al*., Radiat. Meas. **50**, 92 (2013).
   ・Acceleration mechanisms

3. **Ion acceleration in cluster medium in RPA regime (Simulation study)**

4. **Summary**

Why Ion Acceleration using Cluster-Gas Target?

Cluster-Gas target → Sub-critical density plasma



Background gas → Underdense plasma
Density : ~10^{19} cm^{-3}

Cluster → Overdense plasma
Diameter : ~400 nm
Density : ~10^{22} cm^{-3}

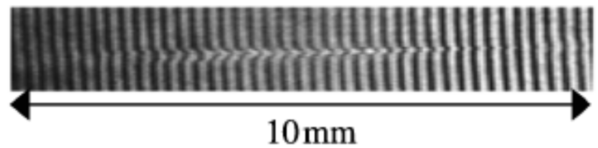
Unique properties of cluster target:

- Self-focusing and long channeling:
  - intensification of focused laser intensity,
  - transport the laser energy to the rear side.

- Copious amounts of high energy electrons:
  - create strong electromagnetic structures inside the target.

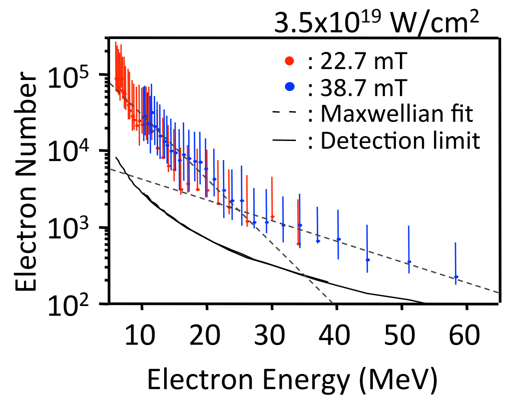
Accelerate ions to higher energies with relatively low laser energy

Self-focusing in cluster media



I. Alexeev et al., PRL **90**, 1034021 (2003).

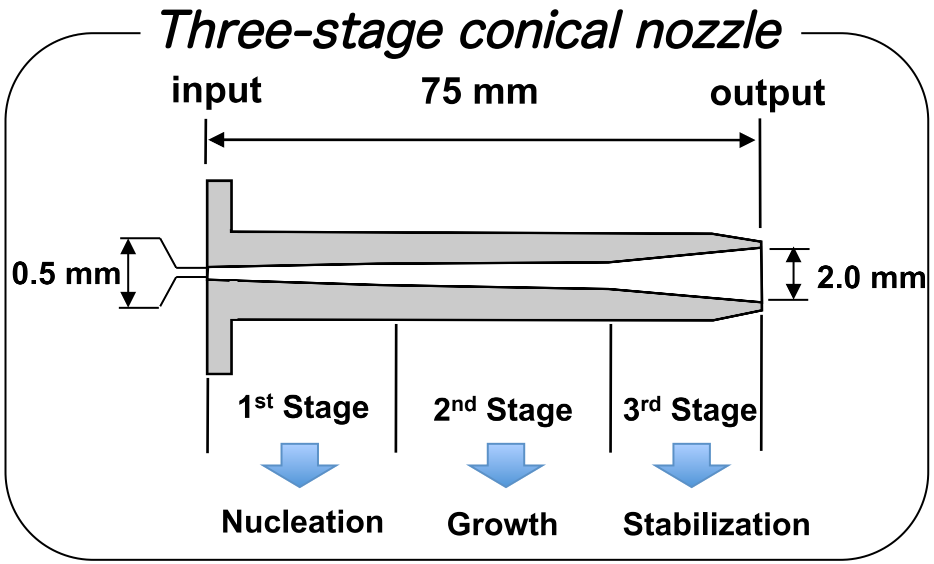
Electron acceleration in cluster media



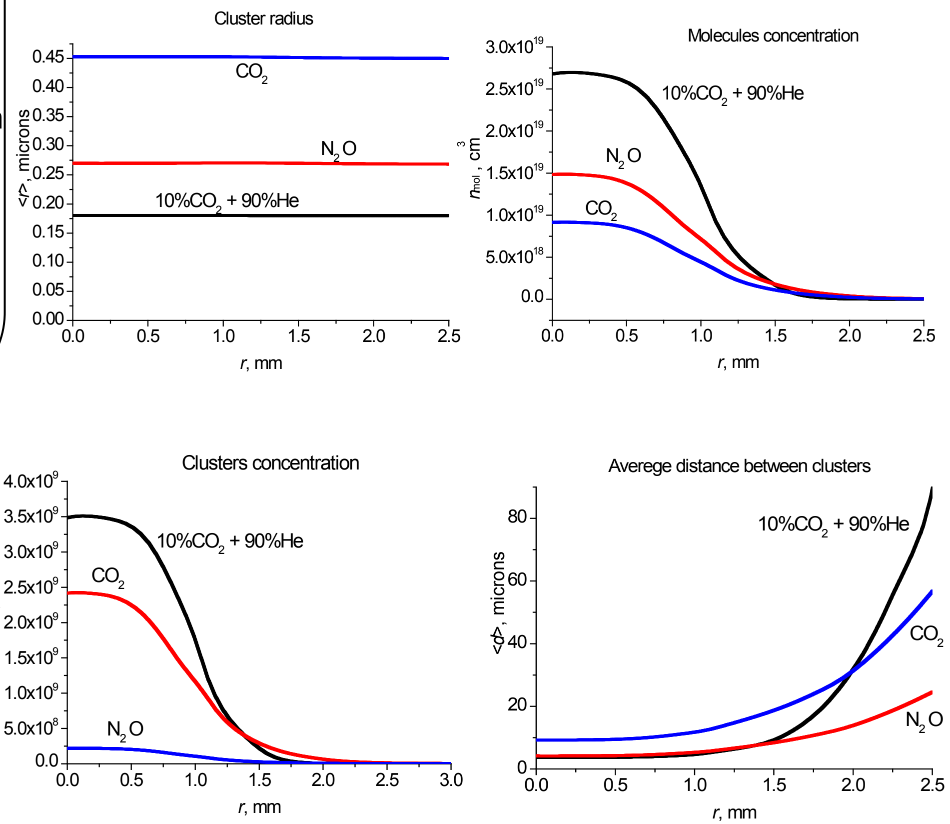
Y. Fukuda et al., PLA **363**, 130 (2007).

Three-Step Conical Nozzle

A.S. Boldarev et al., Rev. Sci. Inst. 77, 083112 (2006).



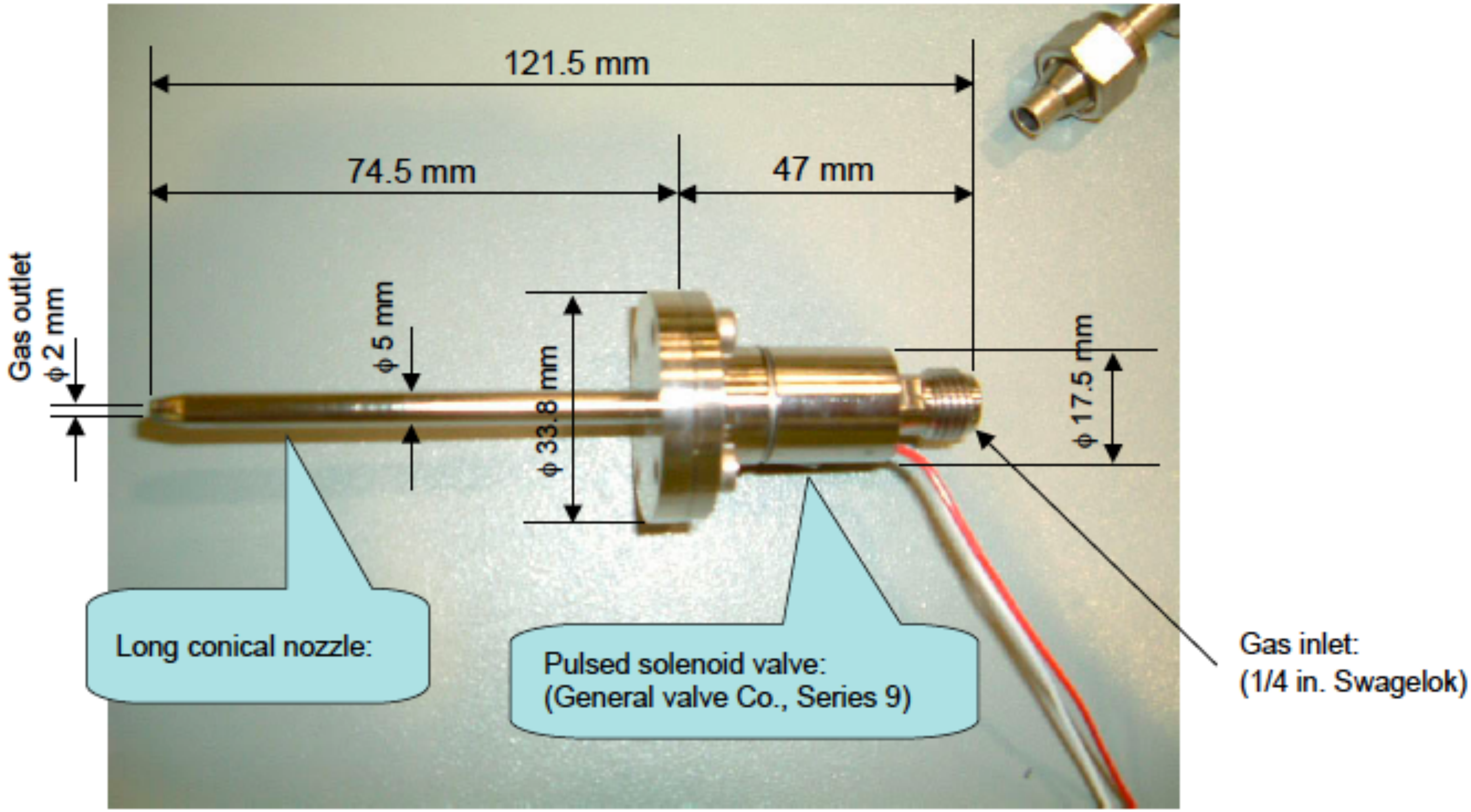
2D-hydrodinamic calculations



- **60-bar mixture of 10 % CO_2 and 90 % He:**
  - **Average cluster diameter: ~400 nm**
    (a root mean square deviation of 0.1 μm)
  - **Background gas concentration: $3x10^{19}$ cm^{-3}**
  - **Average cluster density: $4x10^9$ cm^{-3}**
  - **Average cluster distance: 5 μm**
  - **Dryness: 0.35**

Three-Step Conical Nozzle

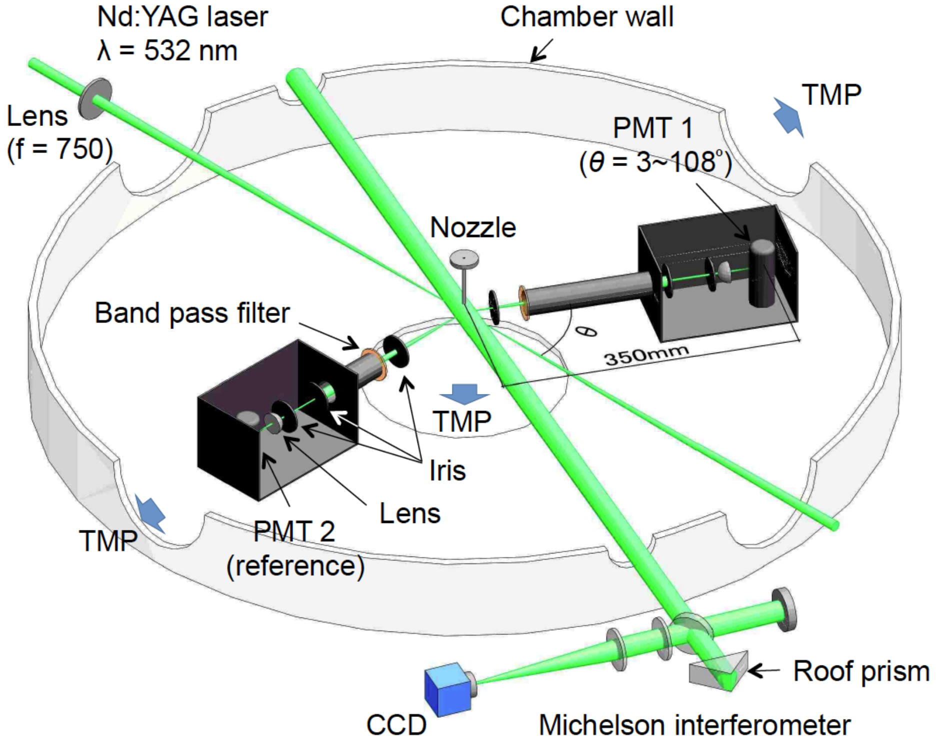
A.S. Boldarev et al., Rev. Sci. Instrum 77, 083112 (2006).



Characterization of Cluster Size using Mie scatter

S. Jinno, et al., Appl. Phys. Lett. **102**, 164103 (2013).
S. Jinno, et al.Opt. Exp. 21, 20656 (2013).

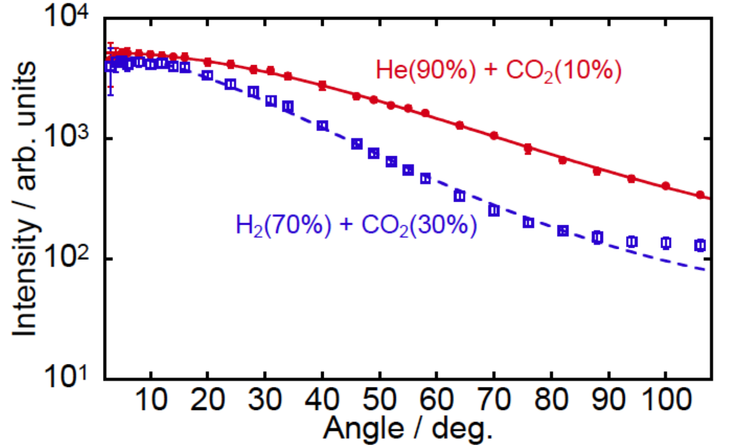
Optical Design



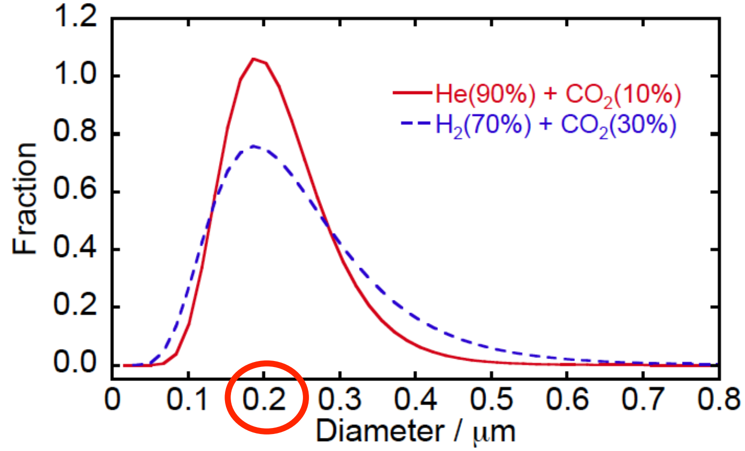
$$I(\theta) = \sum_x F(x,\theta)N(x)$$

$F(x,\theta)$: Angular distribution function
$N(x)$: Size distribution function

Angular distributions of scattered light

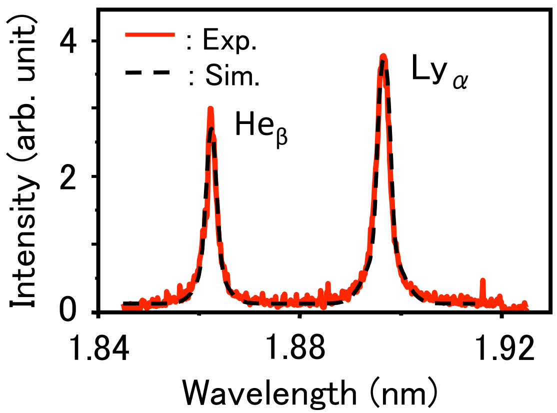


Size distributions of the CO_2 clusters

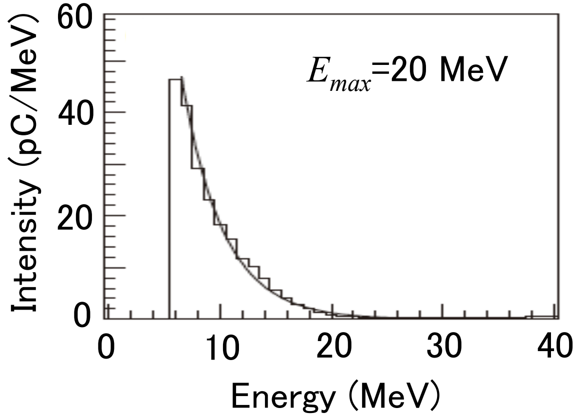


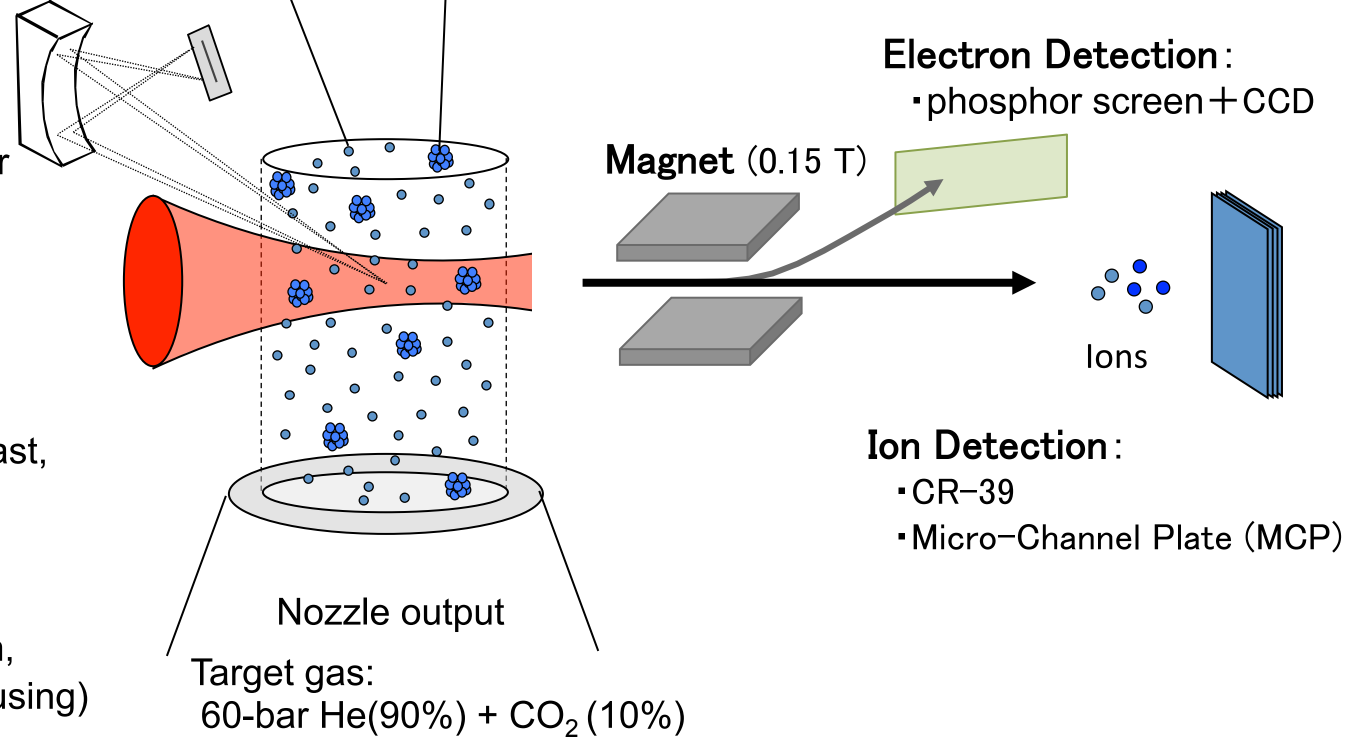
Experimental Setup with 4 TW Laser Facility

Near-Critical Density Plasmas ($0.1n_c$)



Fast Electron Generation

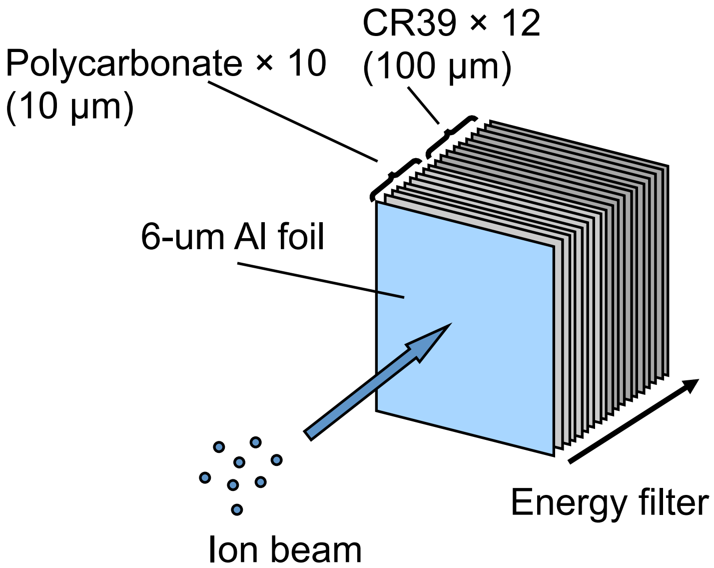




Main laser pulse:

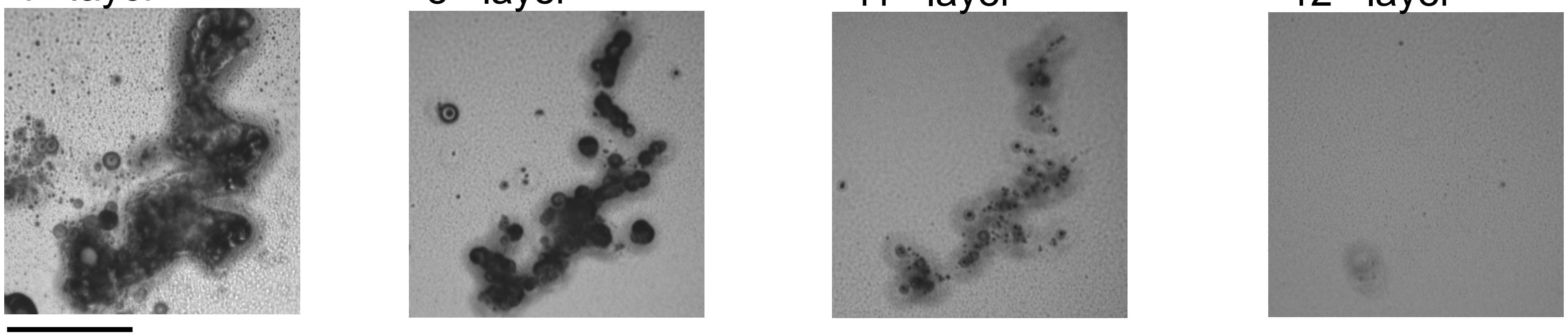
- 40 fs, 150 mJ, 10^{-6} contrast,
- 1 Hz operation
- 30 μm focal spot ($1/e^2$) (F/20 OAP)
- 6×10^{17} W/cm² in vacuum, (~10^{19} W/cm² by self-focusing)

Ion Signals registered in the CR-39 Stack



- Ion pits penetrate through up to 11th layer.

Microscope Image of the CR-39 surfaces



- 6,000 laser shots accumulation.
- Divergence: open angle of 3.4 degree.

Maximum Energies of Accelerated Ions

Since the mixture of He and CO_2 gases are employed in the experiment, the highly charged ions of He^{n+}, C^{n+}, and O^{n+} are the possible candidates for the accelerated ions registered in the CR-39 stack.

Ion signals in CR-39 are discernible up to the 11th layer of 100-μm thick CR-39

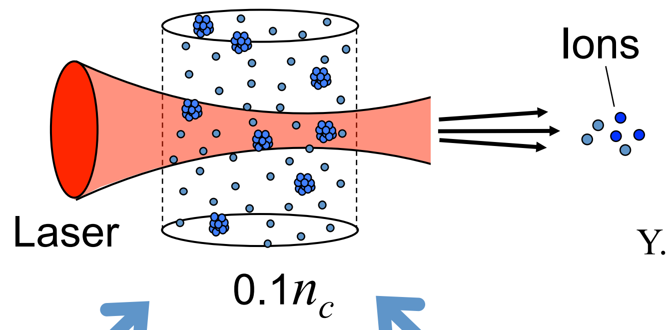
Calculation using the SRIM code

(Proton	10 MeV)	
He^{n+}	10 MeV/u	(40-MeV helium)
C^{n+}	17 MeV/u	(204-MeV carbon)
O^{n+}	20 MeV/u	(320-MeV oxygen)

- Although, at present, we cannot tell the ion species exactly, however, two different sizes of tracks, possibly He^{n+} and C^{n+}/O^{n+}, can be recognized in the microscope images of the CR-39.

Comparison of our Experiment with Others

Cluster-Gas target



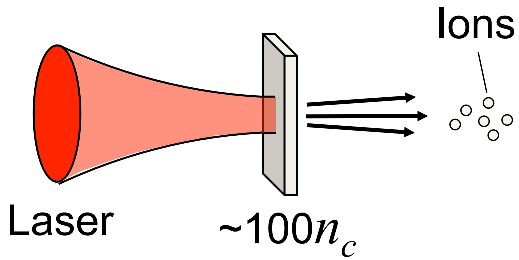
Ion : 10-20 MeV/u
Laser : 150 mJ, 40 fs

Y. Fukuda et al., PRL **103**, 165002 (2009).

Ion Energy : 10 times high!

Laser Energy : ~2300 times low!

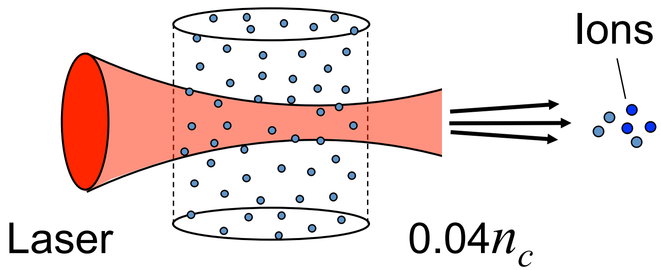
Solid target



Ion : 1.3-1.5 MeV/u
Laser : 120-200 mJ, 55-60 fs

I. Spencer et al., PRE **67**, 046402 (2003).
Y. Oishi et al., PoP **12**, 073102 (2005).

Gas target (He)

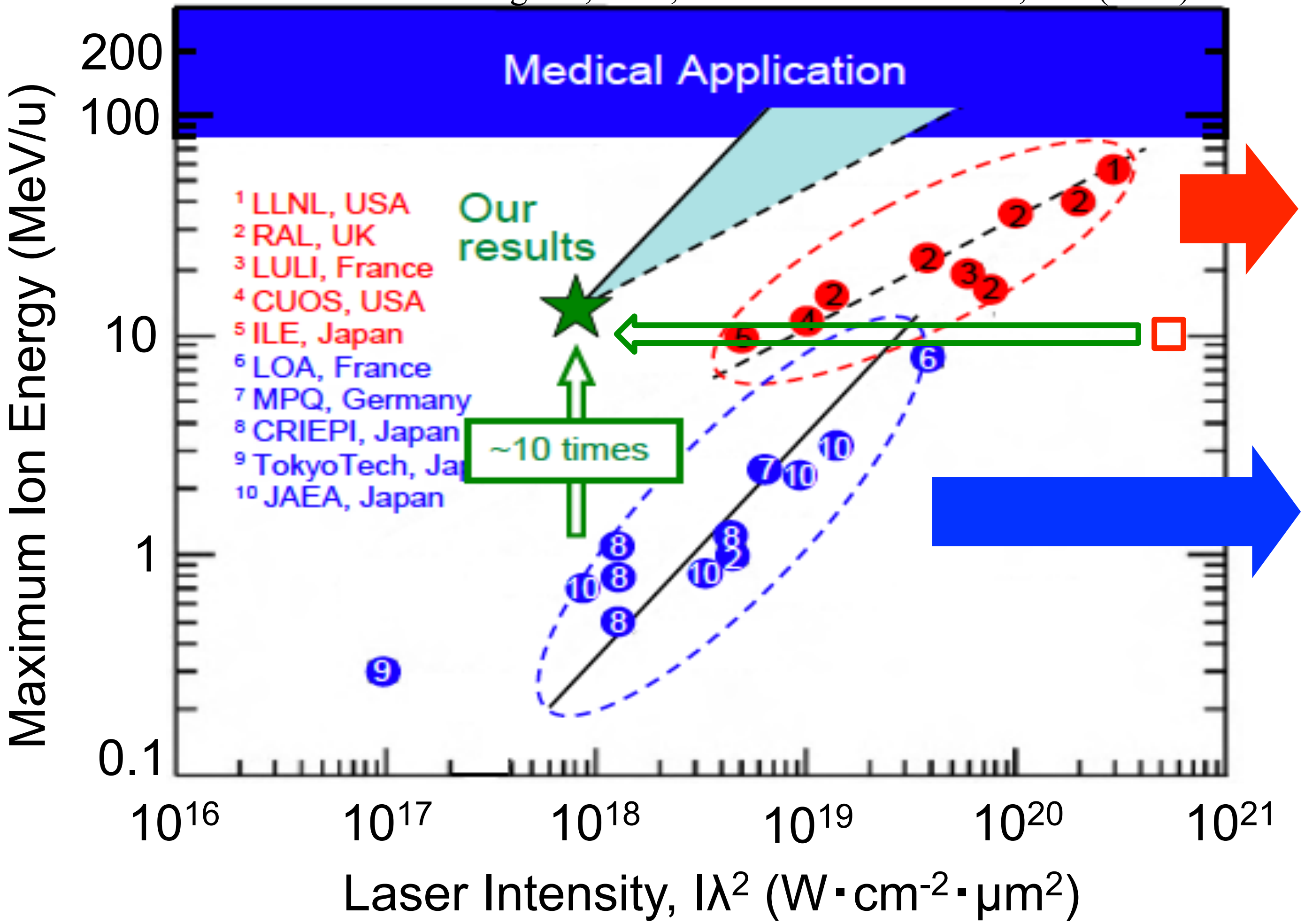


Ion : 10 MeV/u
Laser : 340 J, 1-ps

L. Willingale et al., PRL **96**, 245002 (2006).

Comparison of our experiment with TNSA

M. Borghesi, et al., Fusion Sci. Technol. 49, 412 (2006).



Nd:Glass Laser
- Large scale
- >> J per pulse
- Single shot

Ti:S Laser
- Compact
- < J per pulse
- 10 Hz

Our results belong to a different regime from the TNSA scenario!!

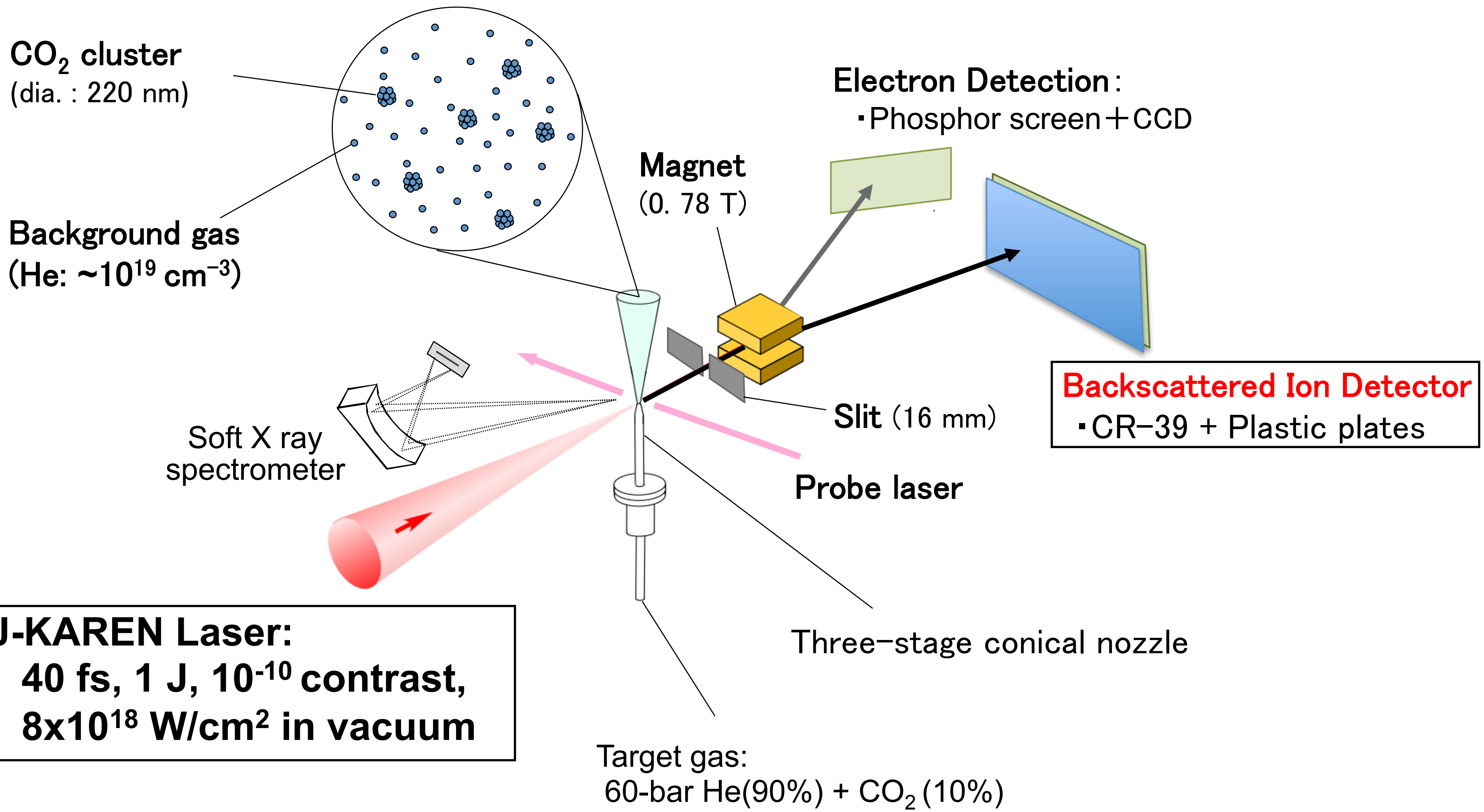
Experimental Setup with J-KAREN Laser

Y. Fukuda *et al*., Radiat. Meas. **50**, 92 (2013).

We have tried to generate more higher energy ions using cluster–gas target

⇧

Need to develop a new ion detection method

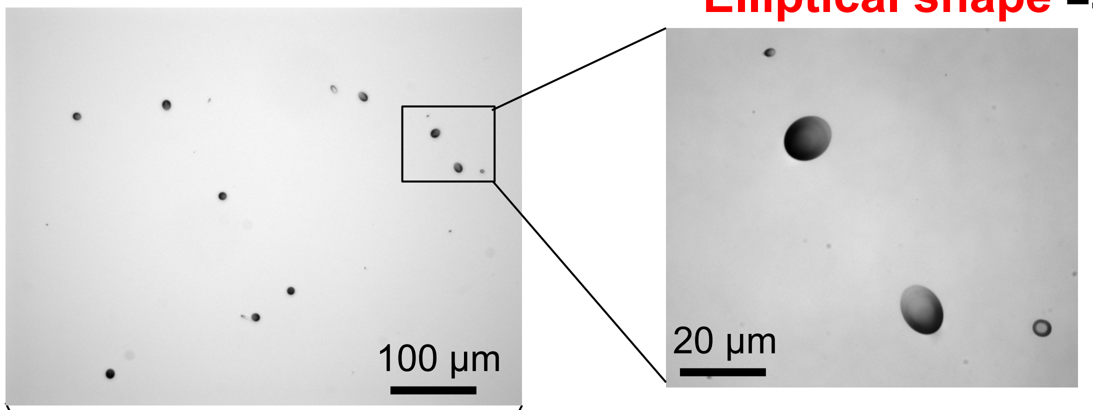


J-KAREN Laser:
40 fs, 1 J, 10^{-10} contrast,
8×10^{18} W/cm^2 in vacuum

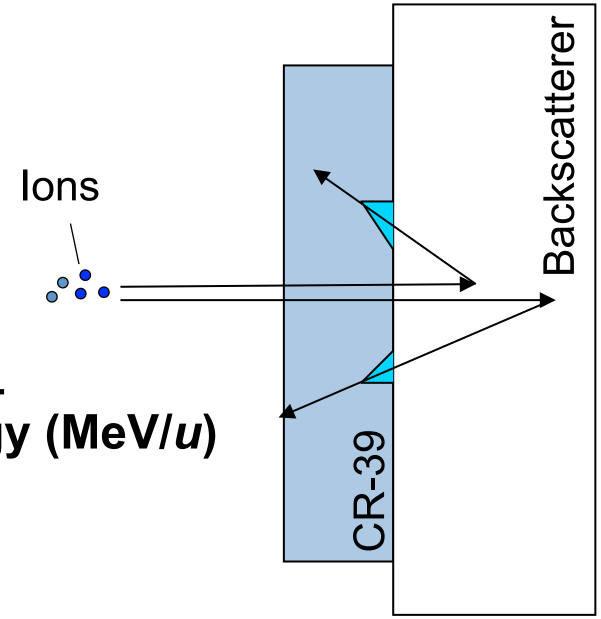
Whole View of Etch Pit Distribution

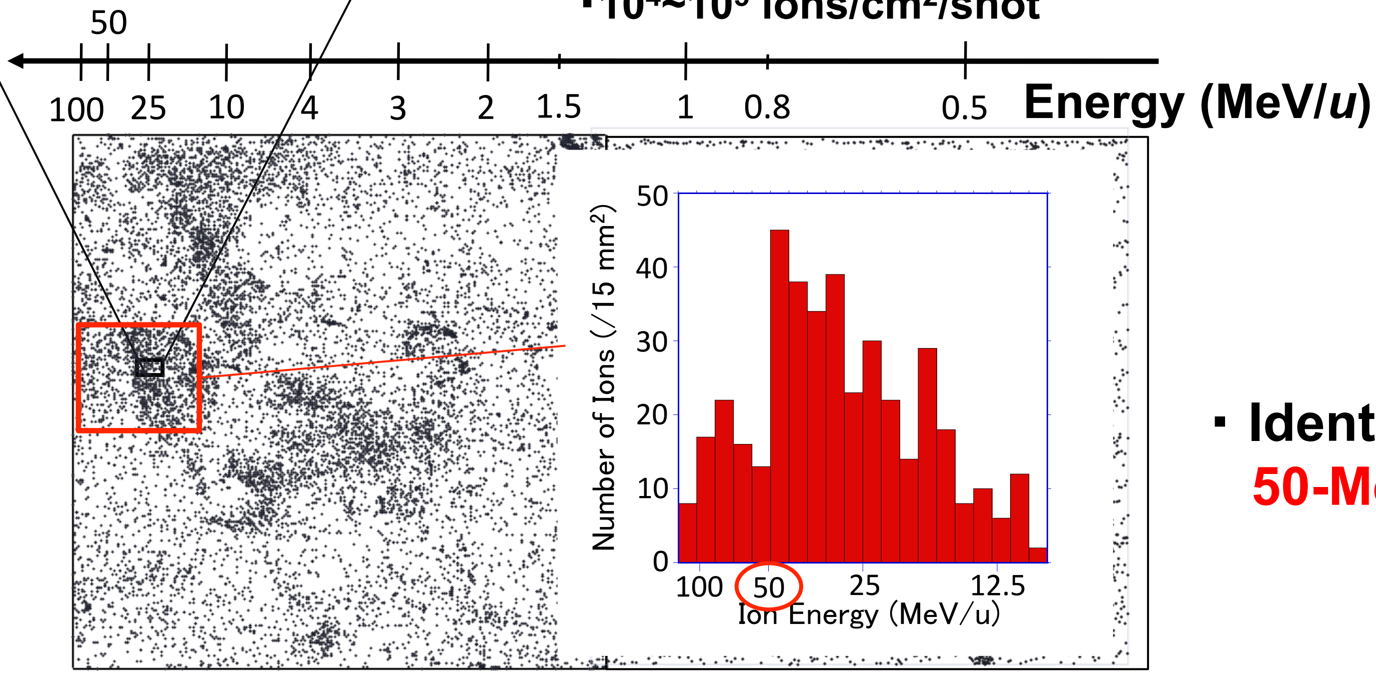
Y. Fukuda *et al.*, Radiat. Meas. **50**, 92 (2013).

Elliptical shape => Ions pass through 100-um CR39, and are backscattered by the backscatterers. Ions go into the CR-39 and create etchable tracks on the rear surface of CR-39.



- **$10\sim10^2$ ions/cm^2/shot**
  ↓ 0.01 %
- **$10^4\sim10^5$ ions/cm^2/shot**





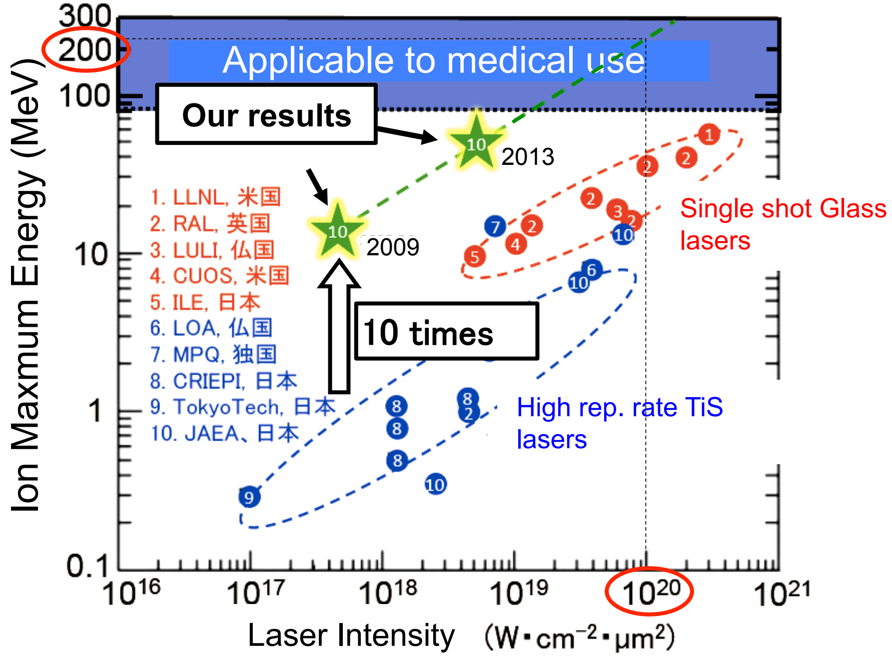
- **Identified:**
  50-MeV/u He ions!!

Different Scenario from TNSA

Experiment

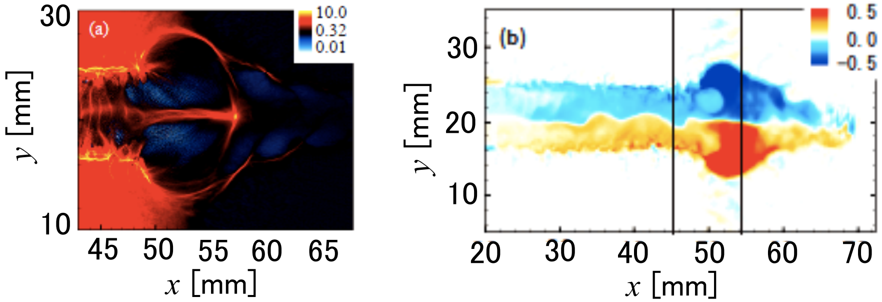
Y. Fukuda *et al.*, Phys. Rev. Lett. **103**, 165002 (2009).
Y. Fukuda *et al.*, Radiat. Meas. **50**, 92 (2013).

Energy scaling



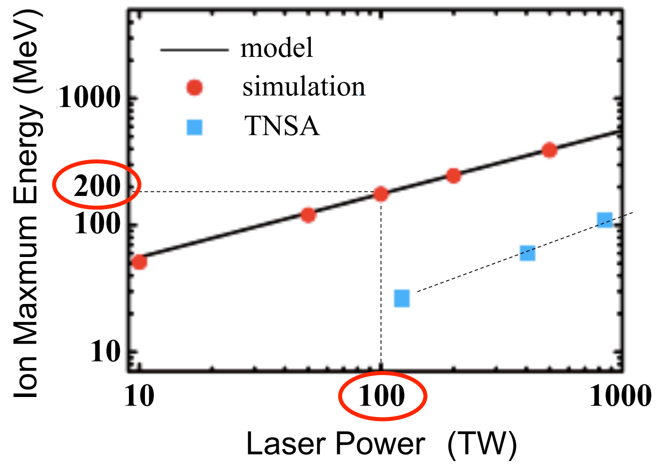
Theory

T. Nakamura *et al.*, Phys. Rev. Lett. **105**, 135002 (2010).



Magnetic vortex in sub-critical density plasmas plays an important role in enhancing accelerated ion energies.

Energy scaling

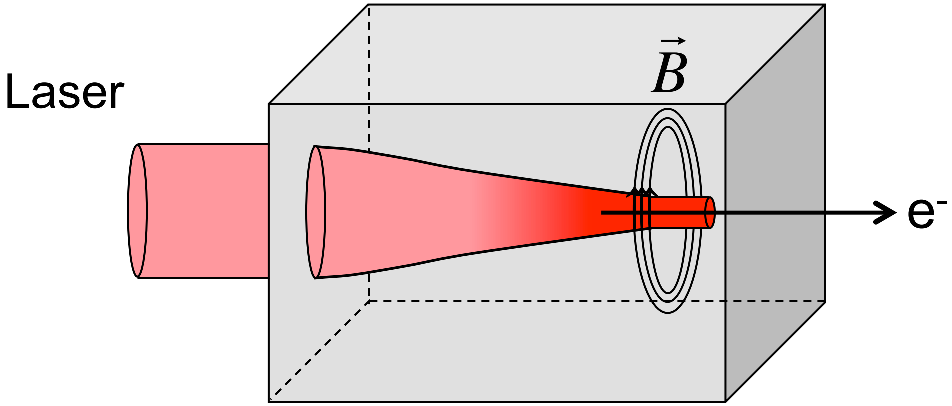


Both experiment and theory predict that …

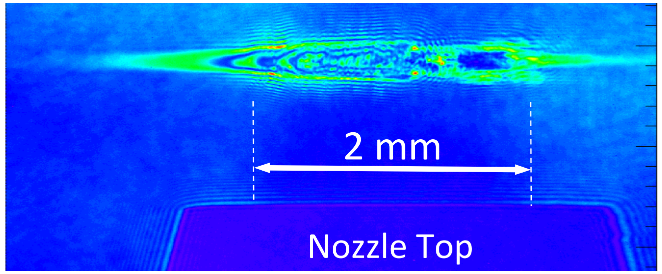
- 100 TW (~10^{20} W/cm^2) class TiS laser can generate 200 MeV ions, applicable to medical use.

Acceleration Mechanism

Near-Critical Density Plasma



Observation of Long Channeling



Shadowgraph Image

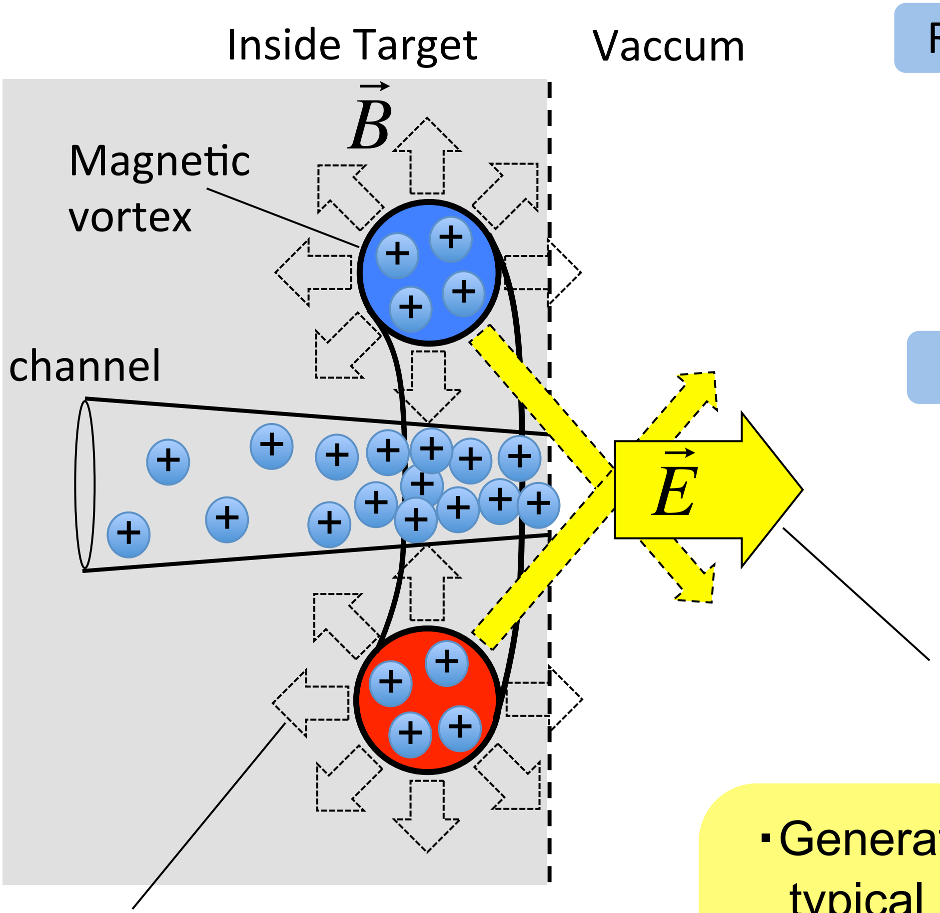
	Experimentally observed?
･Laser channeling due to self–focusing	○
･Fast electron generation by ponderomotive force	○
･Magnetic vortex generation by fast electrons	△

Ampere-Maxwell's equations

$$\nabla \times B = \mu_0 j + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

cf
A.V. Kuznetsov et al., PPR. **27**, 211 (2001).
H. Amitani et al., AIP Conf. Proc. **611**, 340 (2002).
S.V. Bulanov et al., PPR. **31**, 369 (2005).
S.V. Bulanov et al, PRL **98**, 049503 (2007).
S.S. Bulanov et al., PoP **17**, 043105 (2010).
T. Nakamura *et al*., Phys. Rev. Lett. **105**, 135002 (2010).

Acceleration Mechanism



$$P_B = \frac{B^2}{8\pi}$$

P_B = 50 TPa (@B～35 MG)

Role of Magnetic Vortex

Evacuation of electrons inside magnetic vortex due to magnetic pressure

⇩

Magnetic vortex is positively charged

Electric Field caused by Magnetic Pressure

$$E \cong \nabla P_B / en_e = \nabla B^2 / 8\pi en_e$$

Large Electric Field on the Laser Axis

$E \geq$ 10 TV/m (@B～35 MG)

- Generation of large electric field compared to the typical "sheath field" in solid targets (≦1 TV/m)

↓

- Part of electron energy is converted to magnetic field energy ⇨ Origin of efficient ion acceleration

What is the role of the clusters?

Clusters are necessary only for optimal electron density (0.1 n_c)

- enhance the self-channeling and focusing of the laser pulse,
- lead to an increase of the intensity in the plasma,
- fast electrons accelerated in the channel form strong magnetic field with a maximum intensity of about 35 MG
- rather than contributing to ion acceleration via cluster explosions…

Is that really covering all the features??

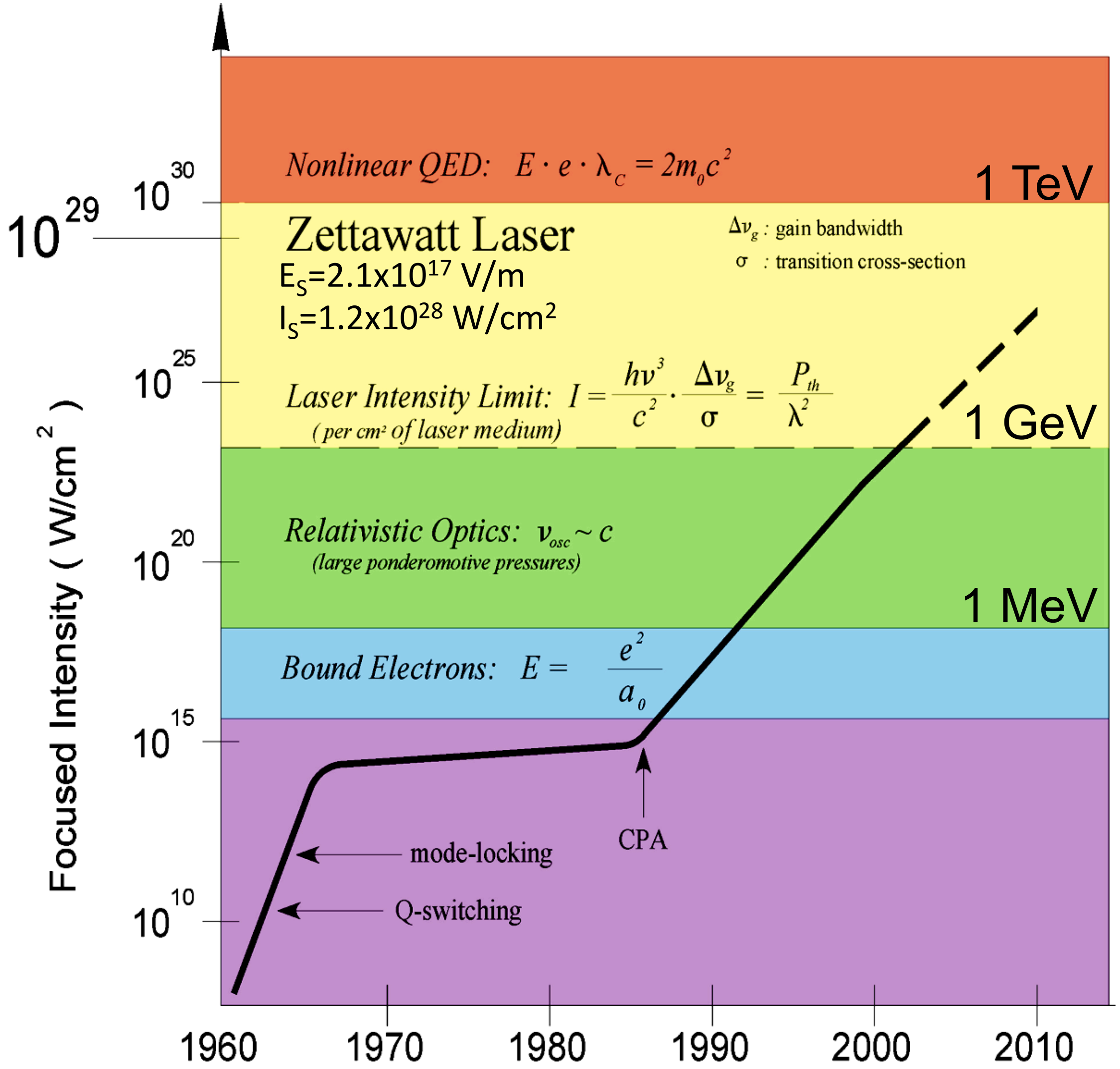
Acceleration Mechanism

In order to further investigate the underlying physical mechanism, we have performed systematic investigations using PIC code…

- Carbon clusters are embedded in background helium gas.

We found that the synergetic interplay of different mechanisms…

High Field Science



Relativistic Ions (Multi-PW lasers)
ELI etc…

Relativistic Electrons (PW lasers)

Atto-Science (TW lasers)

Tajima & Mourou, Phys. Rev. ST 5,031301(2002).
Mourou, Tajima & Bulanov, Rev. Mod. Phys. 78, 309 (2006).

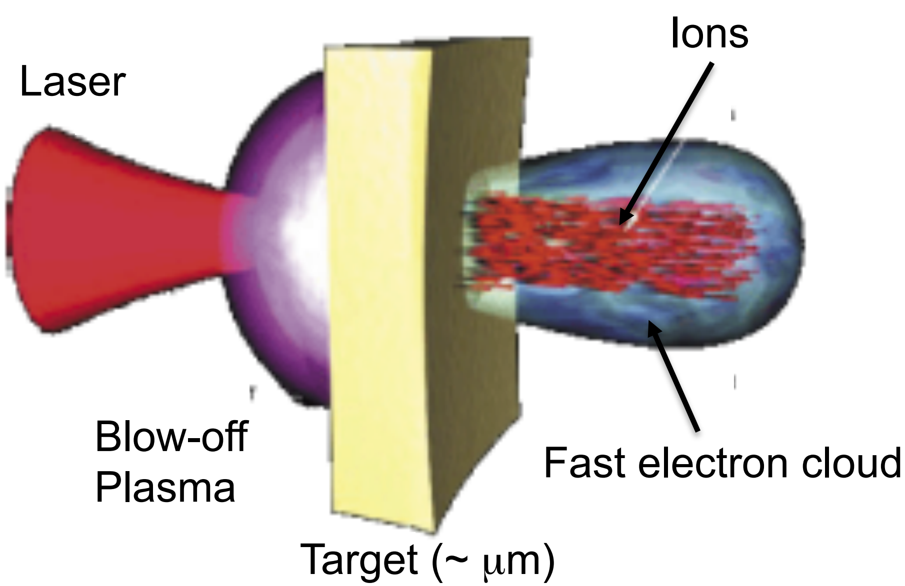
TNSA v.s. RPA (Solid target)

It is now possible to accelerate ions up to several tens of MeV…

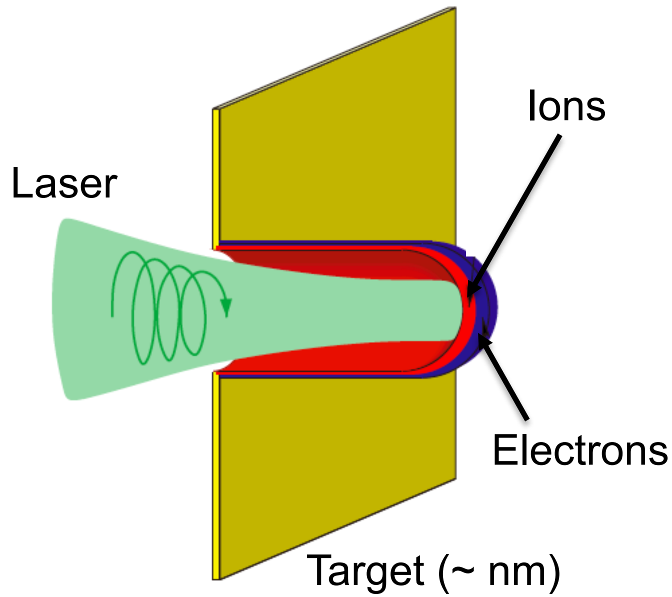
- Laser intensity ~10^{21} W/cm^2
- Relativistic electron regime
  ➡ Photon pressure: $v_e \sim c$

- Laser intensity >10^{23} W/cm^2
- Relativistic ion regime
  ➡ Photon pressure: $v_e \sim v_i \sim c$

TNSA regime



RPA regime



Charge separation fields accelerate ions…
➡ Ions are subject to electron dynamics.
➡ Ion dynamics is hard to control.

Photon pressure accelerate ions…
➡ Both electrons and ion energy become GeV with mono-energetic nature…

Summary and Conclusion

- **Ion acceleration via the interaction of 40 fs, 150 mJ laser pulses with the cluster-gas target is demonstrated.**

⇒ High energy ions, accelerated up to 10-20 MeV/u in the laser propagation direction, are detected in a stack of CR39 detector and a time-of-flight method.

⇩

Tenfold improvement compared to previous experiments

⇒ The 2D-PIC simulations predict that Magnetic-field assisted acceleration work in the near-critical density plasma created by the cluster-gas target.

- **We have developed a new diagnosis method for high energy ion beams using backscattered particles with CR-39 detectors.**

=> This method coupled with a magnetic energy spectrometer is applied to laser-driven ion acceleration experiments using cluster-gas targets.

=> We identified the 50-MeV/u He ions, which energy is beyond the detection threshold limit (10 MeV/u for He) of the CR-39.

Conclusion

- We have investigated the interaction dynamics between high power laser and cluster medium, a kind of random medium.

- Synergetic interplay among different clusters and background gas across the interface between the medium and vacuum can generate directed high energy ions.

▪ Combined acceleration mechanisms (in a relativistic electron regime)
  - Coulomb explosion of carbon cluster
  - Compression & acceleration of background gas ions by the cluster Coulomb explosion
  - Magnetic vortex and pinching
  - Surface sheath acceleration

▪ In a relativistic ion regime
  - ▪ Cooperation between radiation pressure and surface sheath acceleration