# Laser-driven ion accelerations with submicron cluster targets: Contributions of magnetic vortexes

Yuji Fukuda

Department of Advanced Photon Research,
Kansai Photon Science Institute (KPSI),
National Institutes for Quantum and Radiological Science and Technology (QST)

NWP2017,Moscow-St.-Petersburg, Russia
22-28 July 2017

# Collaborators

1. *QST(JAEA)-KPSI, Experiments*
   **M. Tampo, H. Sakaki, A. Yogo, M. Kando, Y. Hayashi, K. Kawase, A.S. Pirozhkov, T. Hori, T. Shimomura, H. Kiriyama, P.R. Bolton, K. Kondo**

2. *Joint Institute of High Temperatures, Russian Academy of Sciences*
   **A.Ya. Faenov, T.A. Pikuz**

3. *Graduate School of Maritime Sciences, Kobe University*: **M. Kanasaki, T. Yamauchi**

4. *Graduate School of Energy Science, Kyoto University*: **R. Matsui, Y. Kishimoto**

5. QST(*JAEA)-TIARA, Development of ion detection methods*
   **S. Kurashima, T. Kamiya**

6. QST(*JAEA)-KPSI, Theory & Simulation*
   **T. Nakamura, T.Zh. Esirkepov, J. Koga, S.V. Bulanov**

7. *Graduate School of Engineering, Osaka University*: **R. Kodama**

8. *Fakultat fur Physik, Ludwig-Maximilians-Universitat Munchen:* **T. Tajima**

9. *The Graduate School for the Creation of New Photonics Industries*: **Y. Kato**

# Outline

QST

1. **Introduction**
   - **Brief overview of laser-driven ion acceleration research**

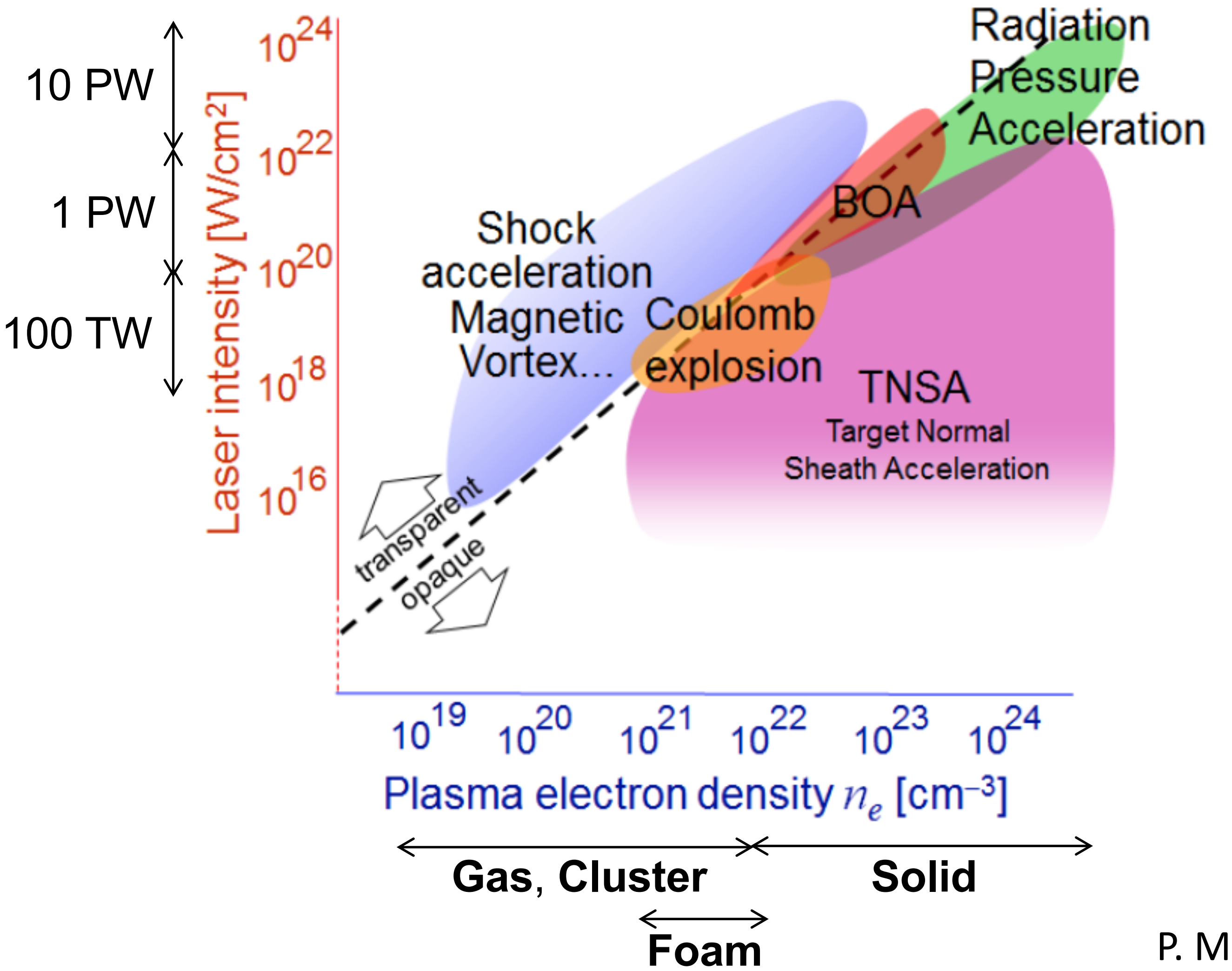
2. **Magnetic vortex acceleration (MVA) in weakly relativistic regime**

3. **Future prospect on MVA in relativistically induced transparency regime**
   (Slides are kindly provided to me by Prof. Alexey Arefiev@UCSD)

4. **Summary**

# Various Ion Acceleration Mechanisms

A number of novel mechanisms are still actively investigated both in theoretically and experimentally.




P. Mackenna, EAAC 2015

# Overview of Ion Acceleration research

QST

**Main goal:**
To achieve over 100 MeV mono-energy protons for medical and industrial applications.

**Recent achievements:**

→ $E_{max}$ = 85 MeV protons via TNSA.

F. Wagner et al., PRL **116**, 205002 (2016).

$E_{max}$ = 93 MeV protons via RPA.

I. J. Kim et al., Phys. Plasmas 23, 070701 (2016).

→ 18 MeV mono-energy pure protons via CSA.

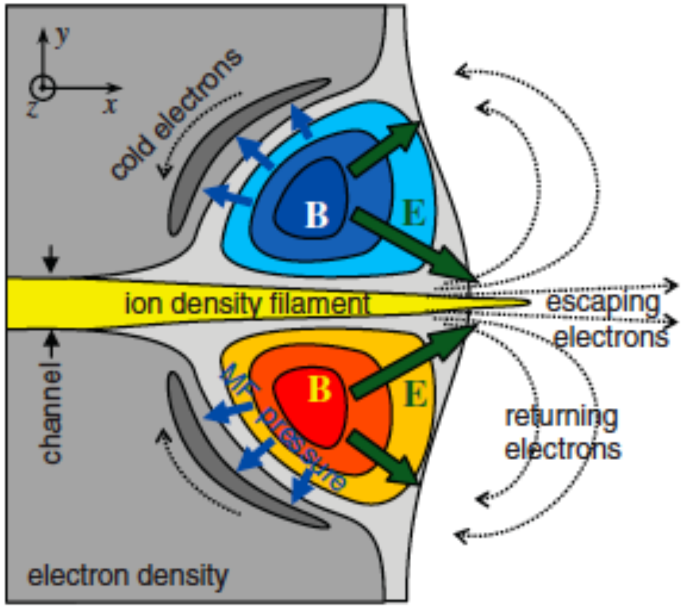
D. Haberberger et al., Nat. Phys 8, 95–99 (2012).

# Magnetic Vortex Acceleration

QST

What is "magnetic vortex acceleration (MVA)"?

- Magnetic vortex structures created at the rear side of the target build up an enhanced electrostatic sheath field, which collimate and accelerate ions.
- Near critical density plasmas ($\lesssim n_c$) are required.



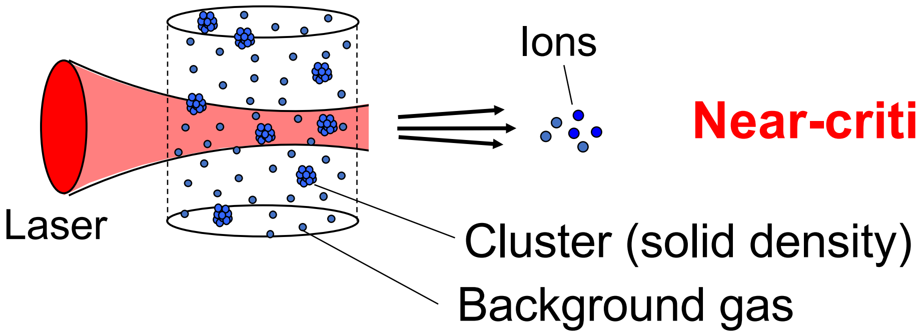

(Quoted from Bulanov and Esirkepov, PRL **98**, 049503 (2007)).


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.S. Bulanov et al., PoP **17**, 043105 (2010).
T. Nakamura et al., PRL **105**, 135002 (2010).

# Various Targets for Ion Acceleration

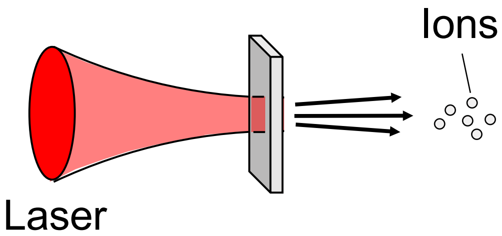
## Cluster Target

・Solid density, submicron sized clusters are embedded in a background gas.




**Near-critical density plasmas (~ $n_c$)**

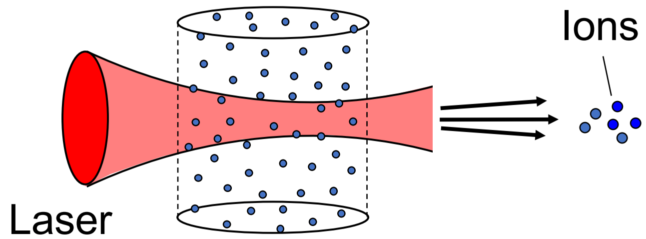
## Solid Target




Overdense Plasmas (>> $n_c$)

・TNSA (mm-thick foils)
・RPA (nm-thick foils)

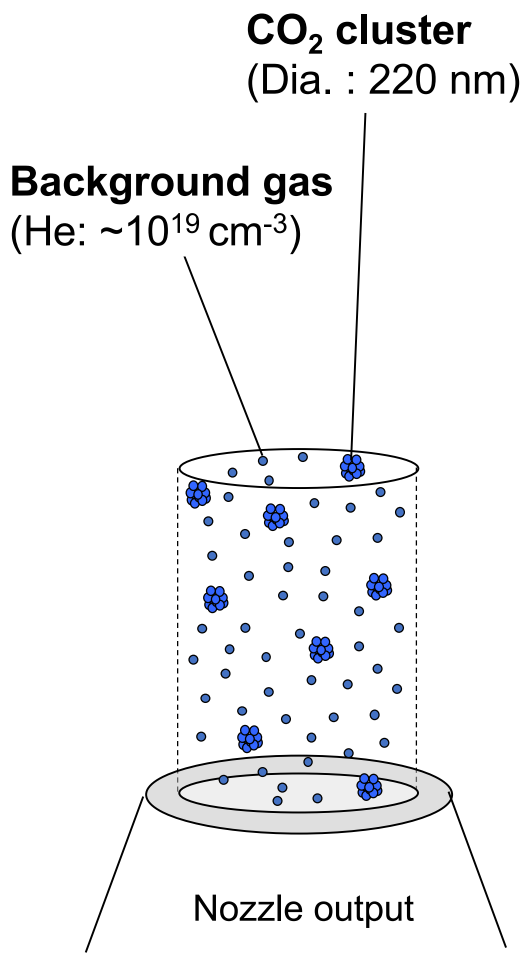
## Gas Target




Underdense Plasmas (<< $n_c$)

・Charge separation
・Collisionless shock

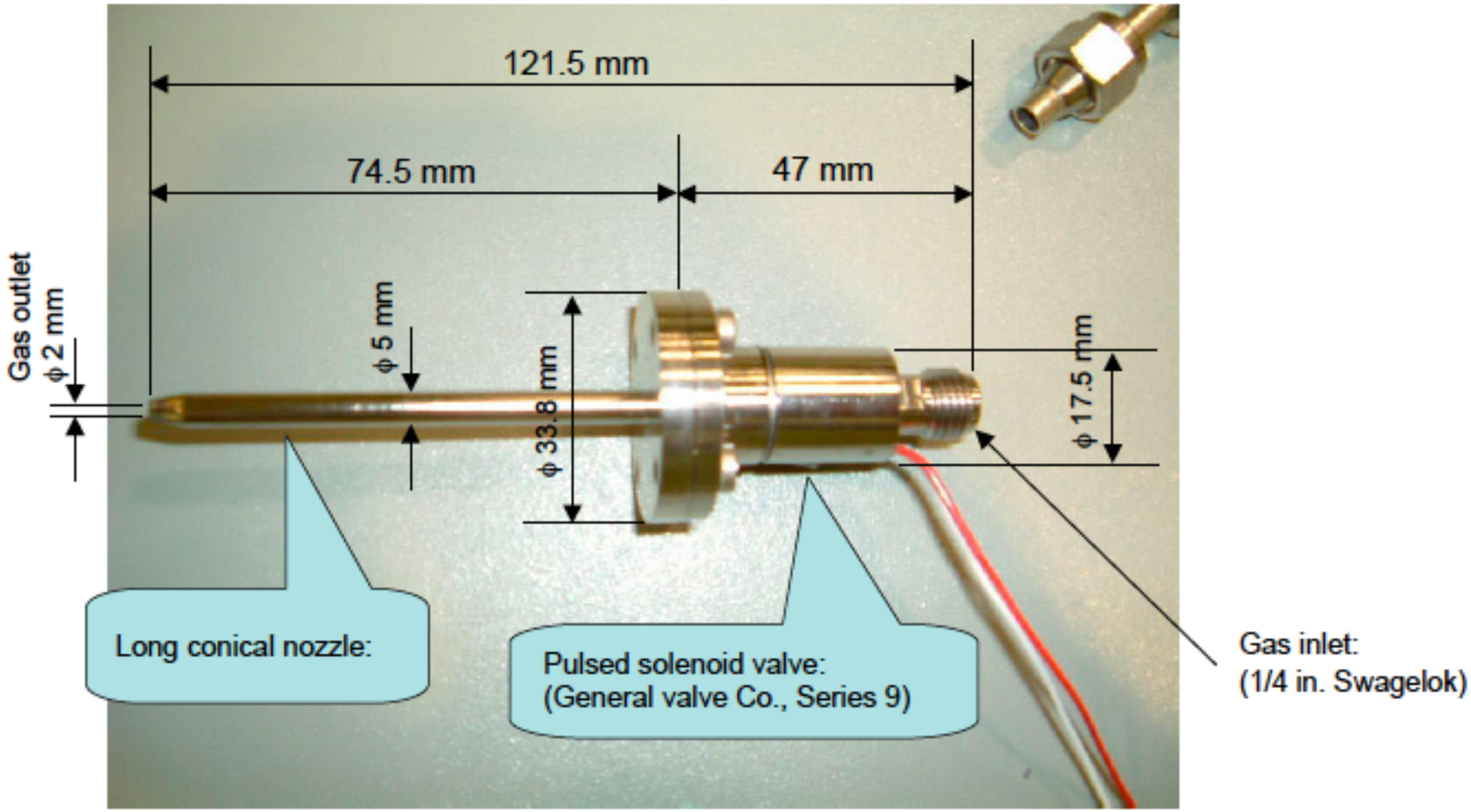
# Experimental Setup




Target gas: 60-bar He(90%) + $CO_2$ (10%)

# Three-Step Conical Nozzle

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

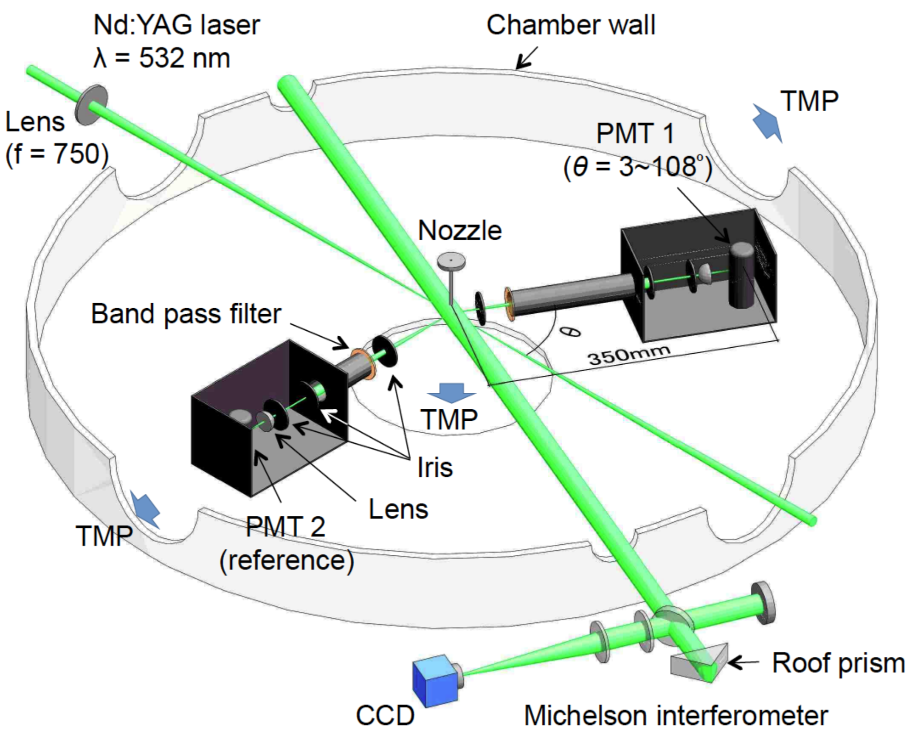


# Characterization of Cluster Size using Mie scattering

QST

S. Jinno, Y. Fukuda et al., Appl. Phys. Lett. **102**, 164103 (2013).

## Optical Design

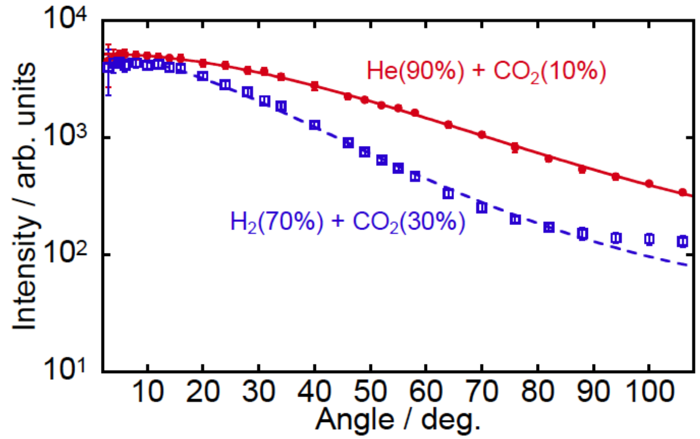



$$I(\theta) = \sum_x F(x,\theta) N(x)$$

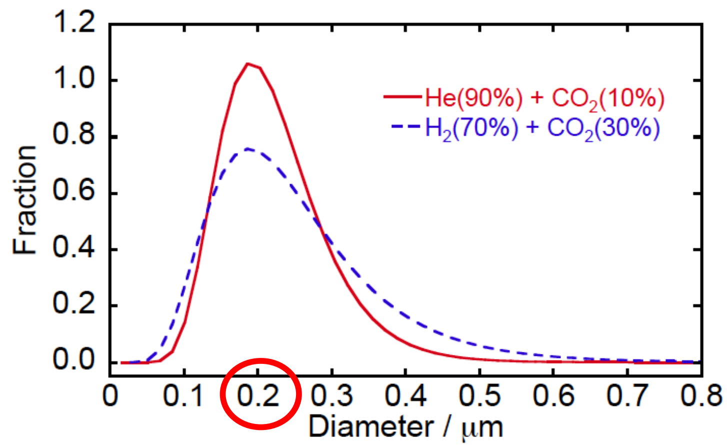
$F(x,\theta)$ : Angular distribution function

$N(x)$ : Size distribution function

Angular distributions of scattered light

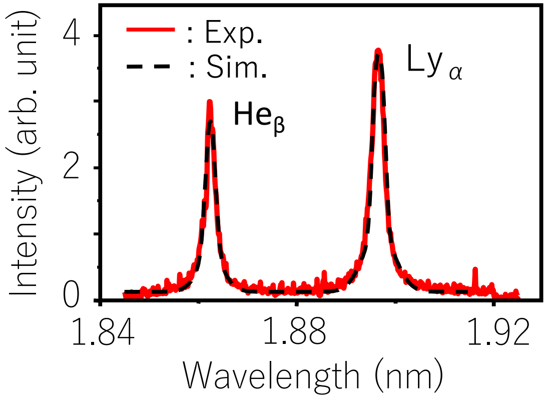



Size distributions of the $CO_2$ clusters

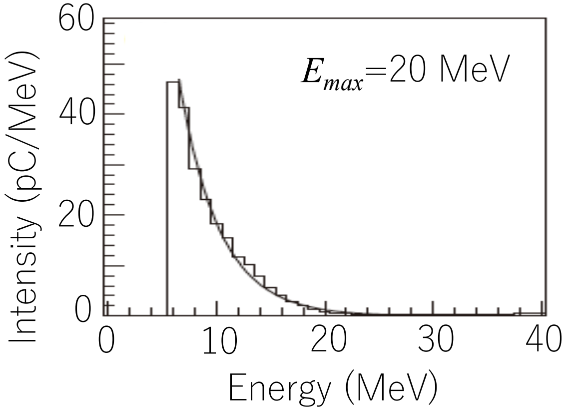


# Experimental Setup

**Near-Critical Density Plasmas** $(0.1n_c)$




**Fast Electron Generation**



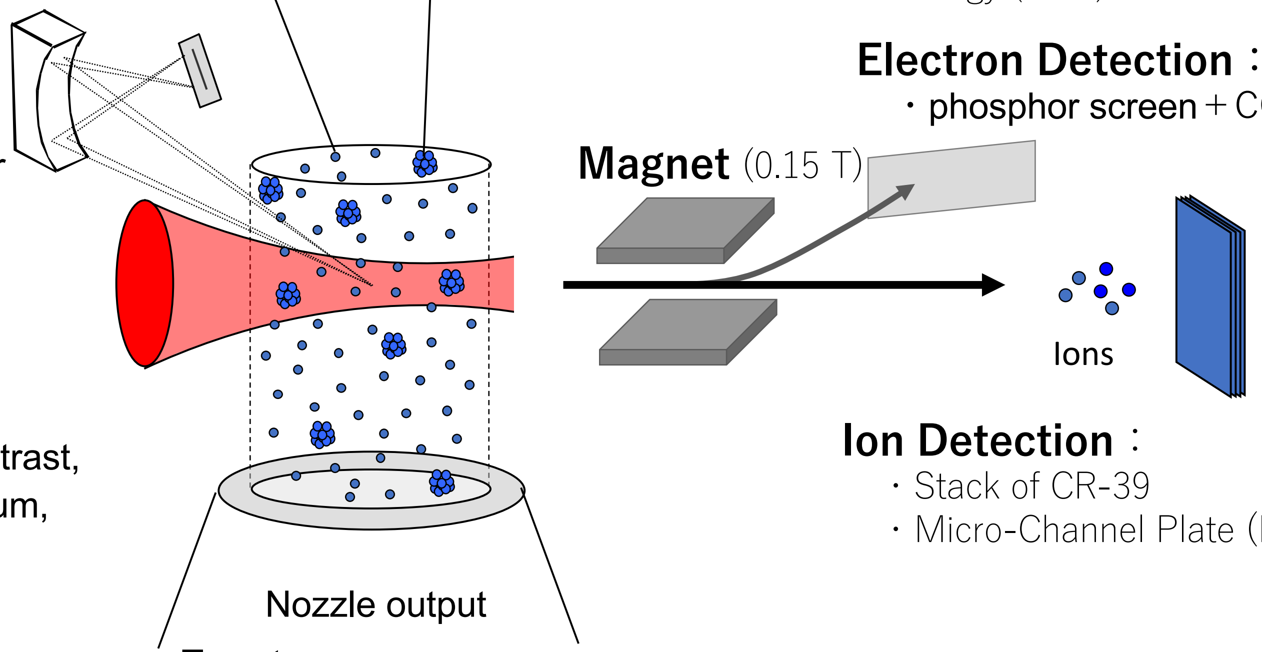

**$CO_2$ cluster**
(Dia. : 220 nm)

**Background gas**
(He: ~$10^{19}$ $cm^{-3}$)

Soft X ray spectrometer

**Electron Detection**：
・phosphor screen＋CCD

**Magnet** (0.15 T)



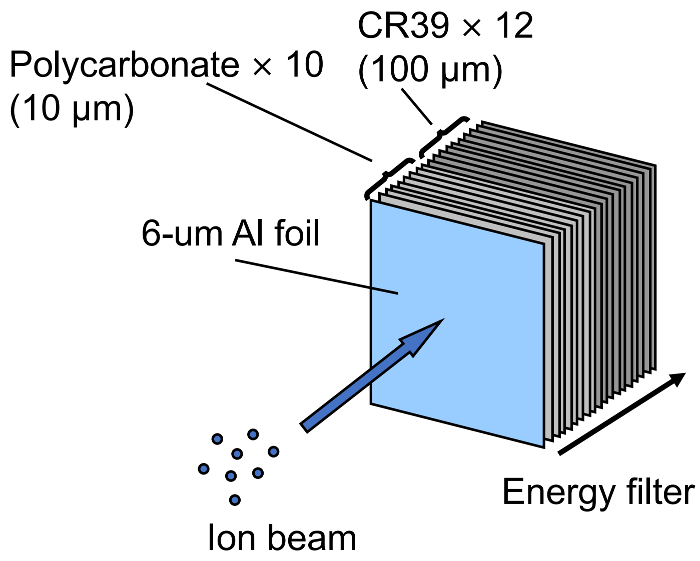

**Ion Detection**：
・Stack of CR-39
・Micro-Channel Plate (MCP)

Main laser pulse:
40 fs, 150 mJ, $10^{-6}$ contrast,
6X$10^{17}$ W/cm$^2$ in vacuum,
1 Hz operation
30 μm focal spot (1/e$^2$)

Nozzle output

Target gas:
60-bar He(90%) + $CO_2$ (10%)

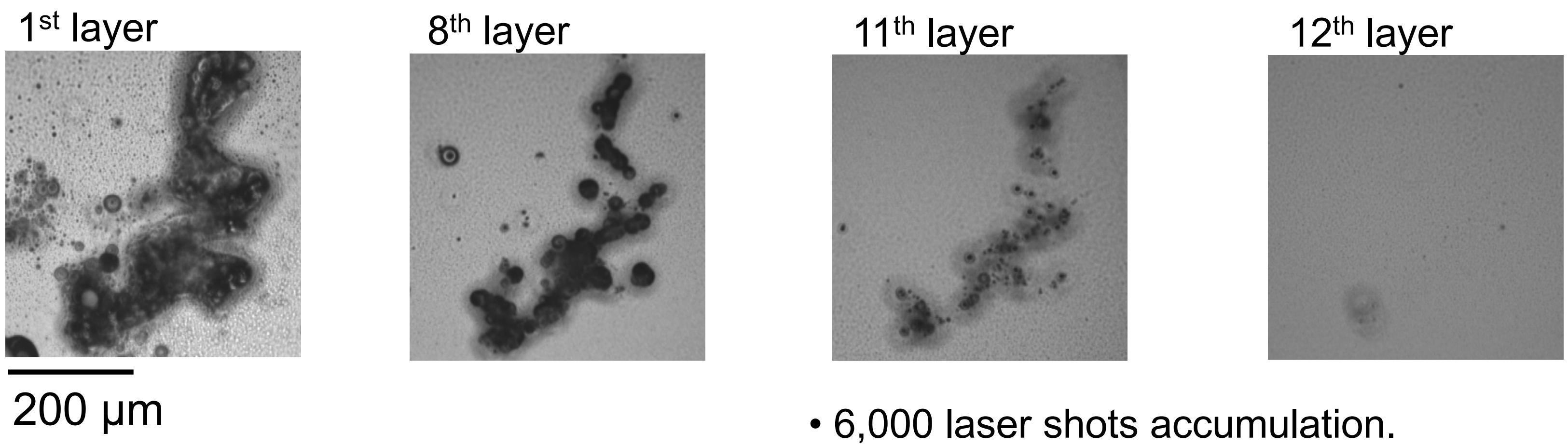
# Ion Signals registered in the CR-39 Stack




- Ion pits penetrate through up to 11th layer.

| | |
|---|---|
| $He^{n+}$ | 10 MeV/u |
| $C^{n+}$ | 17 MeV/u |
| $O^{n+}$ | 20 MeV/u |

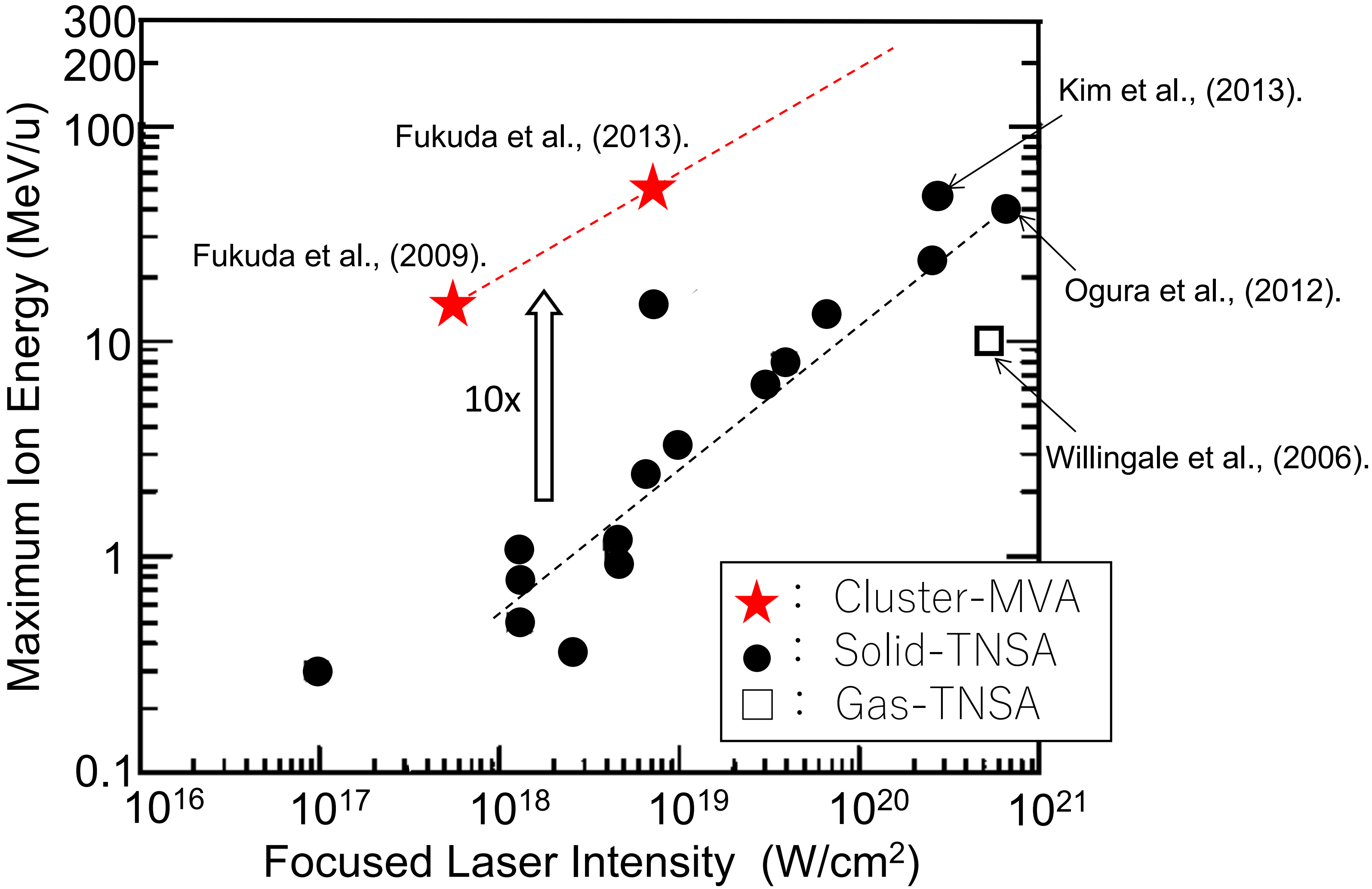
**Microscope Image of the CR-39 surfaces**




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

# Ion Acceleration using Cluster Targets

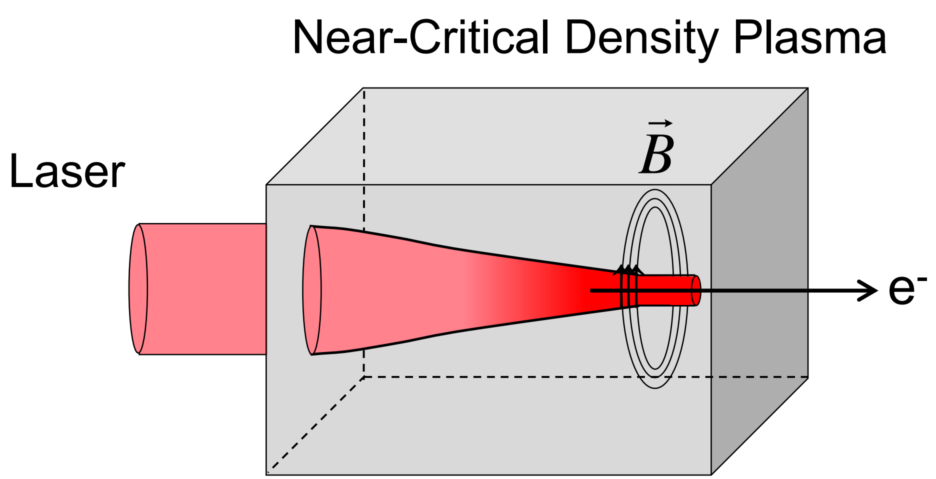
QST

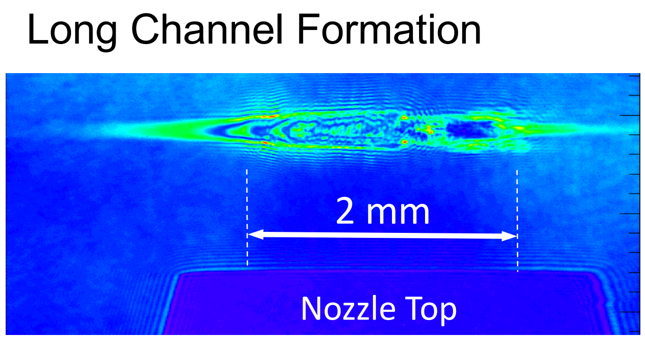




1. Y. Fukuda et al., PRL **103**, 165002 (2009).
2. Y. Fukuda et al., Radiat. Meas. **50**, 92 (2013).

# Acceleration Mechanism



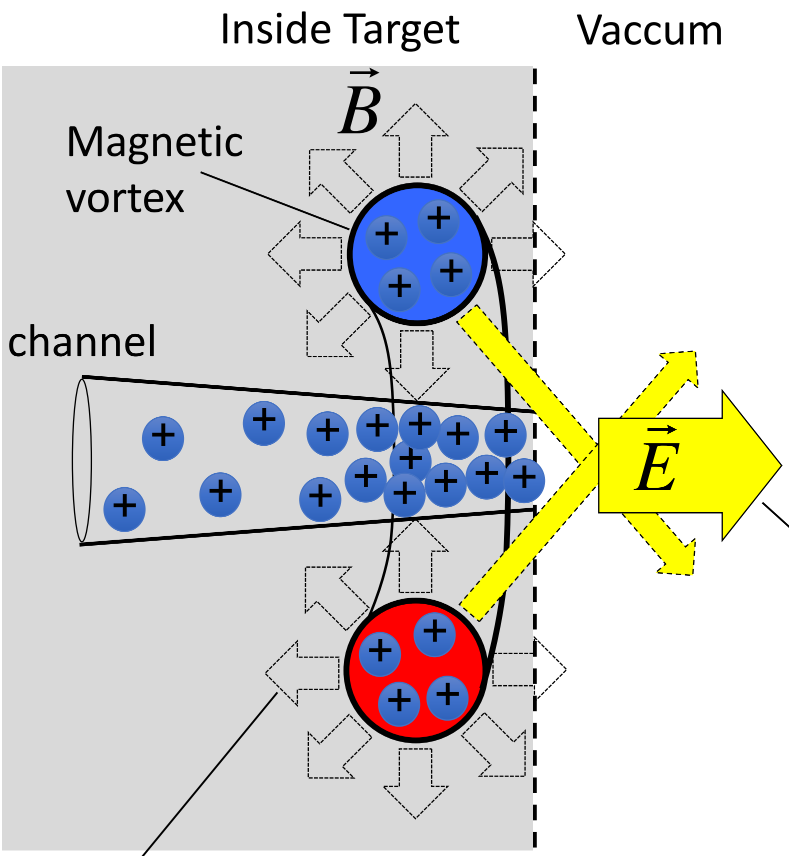
Shadowgraph Image

- Laser channeling due to self-focusing
- Fast electron generation by ponderomotive force
- Magnetic vortex structure formation by fast electrons

**Ampere-Maxwell's equations**

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

# 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

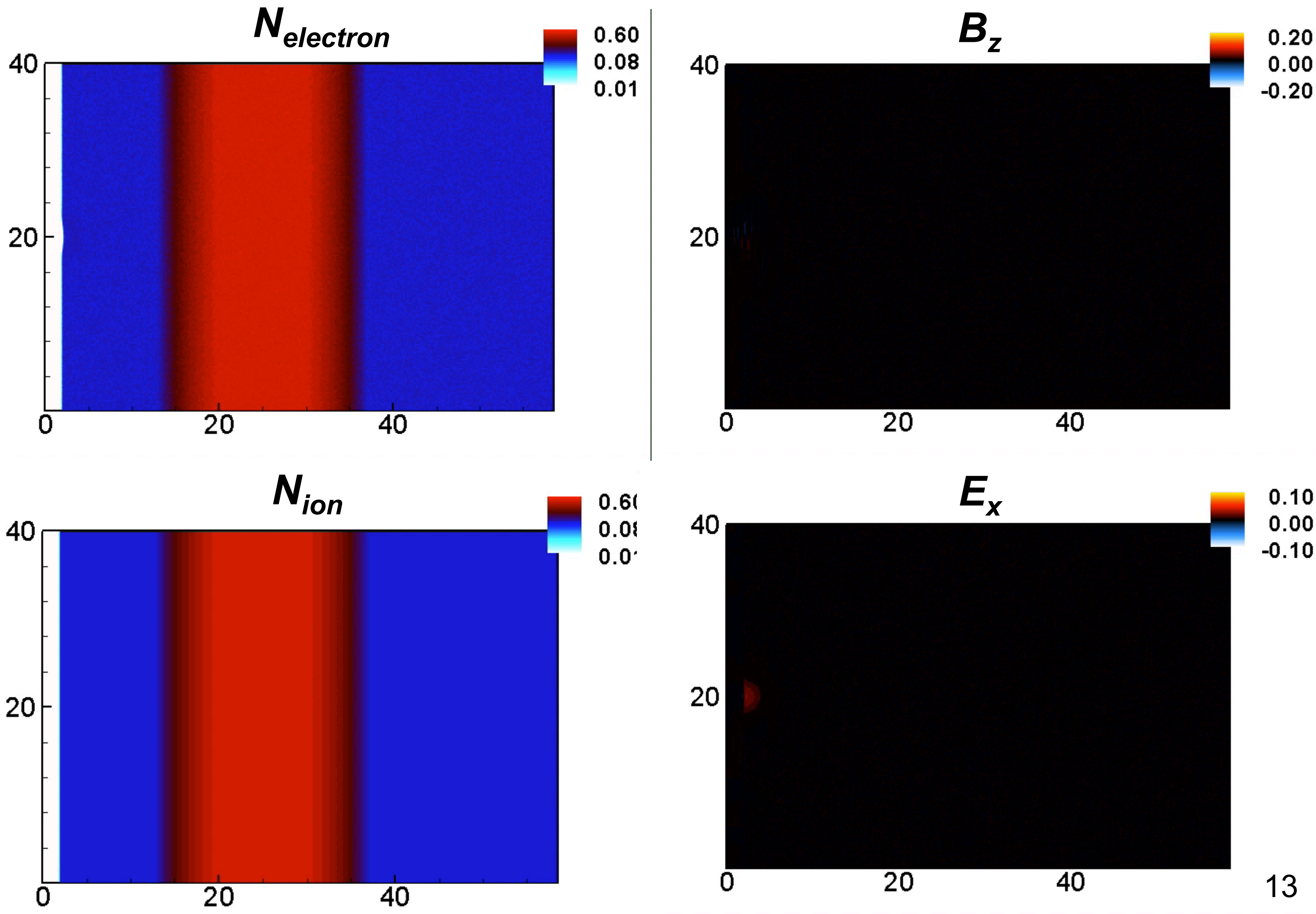
**Electric Field caused by Magnetic Pressure**

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

Electric Field on the Laser Axis

$E$ ≥ 10 TV/m (@$B$～35 MG)

- Electric field in MVA : ≥ 10 TV/m
- Typical "sheath field" in TNSA（≤ 1 TV/m)



$N_{electron}$
0.60
0.08
0.01
$B_z$
0.20
0.00
-0.20
$N_{ion}$
$E_x$
0.10
0.00
-0.10
0
20
40

# Acceleration Mechanism

QST

Time evolution of field energy (R. Matsui, Y. Kishimoto (2014))

Available after publication

Part of electron energy is converted to magnetic field energy

⇨ Origin of efficient ion acceleration in MVA

# Near Future of Magnetic Vortex Acceleration in Relativistically Induced Transparency Regime ($I > 10^{22}$ W/cm$^2$)

**(Slides are kindly provided to me by Prof. Alexey Arefiev@UCSD)**

**Point:**

- Main drawback of MVA in weakly relativistic regime:

  ⇨ The number of accelerated ions is small because of its optimal target density ~$0.1n_c$

Available after publication

# Setup for ion acceleration

Courtesy of A. Arefiev (2017)

Available after publication

# Magnetic & electric field structure

Courtesy of A. Arefiev (2017)

Available after publication

# Collimated proton beam

Courtesy of A. Arefiev (2017)

Available after publication

# Proton spectra

Courtesy of A. Arefiev (2017)

Available after publication

# Summary and Conclusion

**1. Magnetic vortex (~35 MG) in weakly relativistic regime:**

- Ceated at the rear side of the near critical density plasma (~0.1nc)
- Due to a fast electron beam
- Contribute to create a strong accelerating field structure (~10 TV/m)

- Enhancement of accelerated ion energies up to 10-20 MeV/u at ~$10^{18}$ W/cm$^2$

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

**2. Magnetic vortex (~300 kT = ~3 GG) in relativistically induced transparency regime:**

Available after publication

**3. In MVA, part of fast escaping electron energy is converted to magnetic field energy, and is utilized to create a strong accelerating field structure.**