Development of submicron-size hydrogen cluster targets for impurity-free laser-driven proton sources

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Outline

1. Introduction
   Coulomb explosion of clusters@10^{22} W/cm^2 regime

2. Development of submicron-size hydrogen cluster targets

3. 2D-PIC simulations for Coulomb explosion of submicron-size clusters@10^{22} W/cm^2 regime

4. Summary

Re-thinking: Coulomb explosion of clusters

From a view point of applications of laser-driven proton beam to laboratory nuclear physics, cancer therapy, etc.,,

Ion acceleration mechanism should be simple enough to ensure "stability"…

Re-thinking: Coulomb explosion of clusters

Ex)
Magnetic-field assisted ion acceleration with cluster targets

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

Pros
- Tenfold enhancement of accelerated ion energy compare to TNSA experiments
- High rep. rate
- Debris free

↓
- Physical process-Scientific interests

Cons
- Unstable-highly nonlinear phenomena
- Small number of accelerated ions

↓
- Not suitable for applications

One of possible solutions for 100 MeV proton beams suitable for applications

↓

Coulomb explosion of H_2 clusters @10^{22} W/cm^2

Re-thinking: Coulomb explosion of clusters

K. Nishihara *et al.*, NIM A **464**, 98 (2001).

Maximum ion energy obtainable from "pure" Coulomb explosion:

$$E_{\max} = 300 Z^2 \times \left(\frac{n_0}{5 \times 10^{22}\,\mathrm{cm}^{-3}} \right) \left(\frac{R_0}{1\mu\mathrm{m}} \right)^2 = 276 Z^2 \times R_0^2(\mu\mathrm{m})\ \mathrm{MeV}$$

Ex) H_2 cluster

10 keV (dia. 10 nm) <= good for D-D fusion (T. Ditmire et al., Nature **398**, 489 (1999).)
0.69 MeV (dia. 100 nm)
44 MeV (dia. 800 nm) <= good to trigger nuclear reactions
276 MeV (dia. 2000 nm) <= good for cancer therapy

Laser intensity required to <u>remove all electrons</u> from clusters:

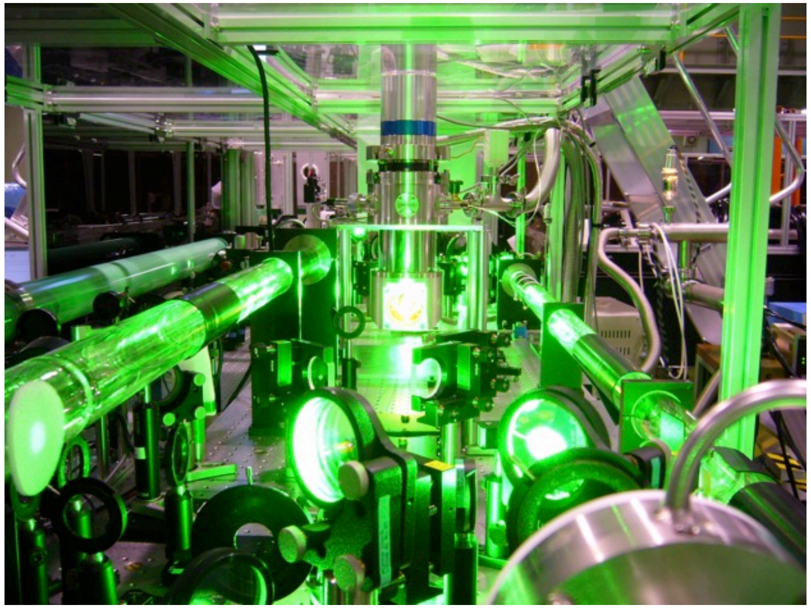
$$a_0 = 34\sqrt{2} \times \sqrt{\frac{4.6 \times 10^{22}\,\mathrm{cm}^{-3}}{5 \times 10^{22}\,\mathrm{cm}^{-3}}} \left(\frac{R_0}{1\mu\mathrm{m}} \right) = 46.11 \times R_0(\mu\mathrm{m})$$

Ex) H_2 cluster

$1\mathrm{x}10^{17}$ W/cm^2 (dia. 10 nm) <= good for D-D fusion (T. Ditmire et al., Nature **398**, 489 (1999).)
$1\mathrm{x}10^{19}$ W/cm^2 (dia. 100 nm)
$7\mathrm{x}10^{20}$ W/cm^2 (dia. 800 nm) <= good to trigger nuclear reaction
$4\mathrm{x}10^{21}$ W/cm^2 (dia. 2000 nm) <= good for cancer therapy

The "J-KAREN" : Intense Laser Facility at JAEA-KPSI

The 1st PW-class OPCPA/Ti:sapphire hybrid laser system



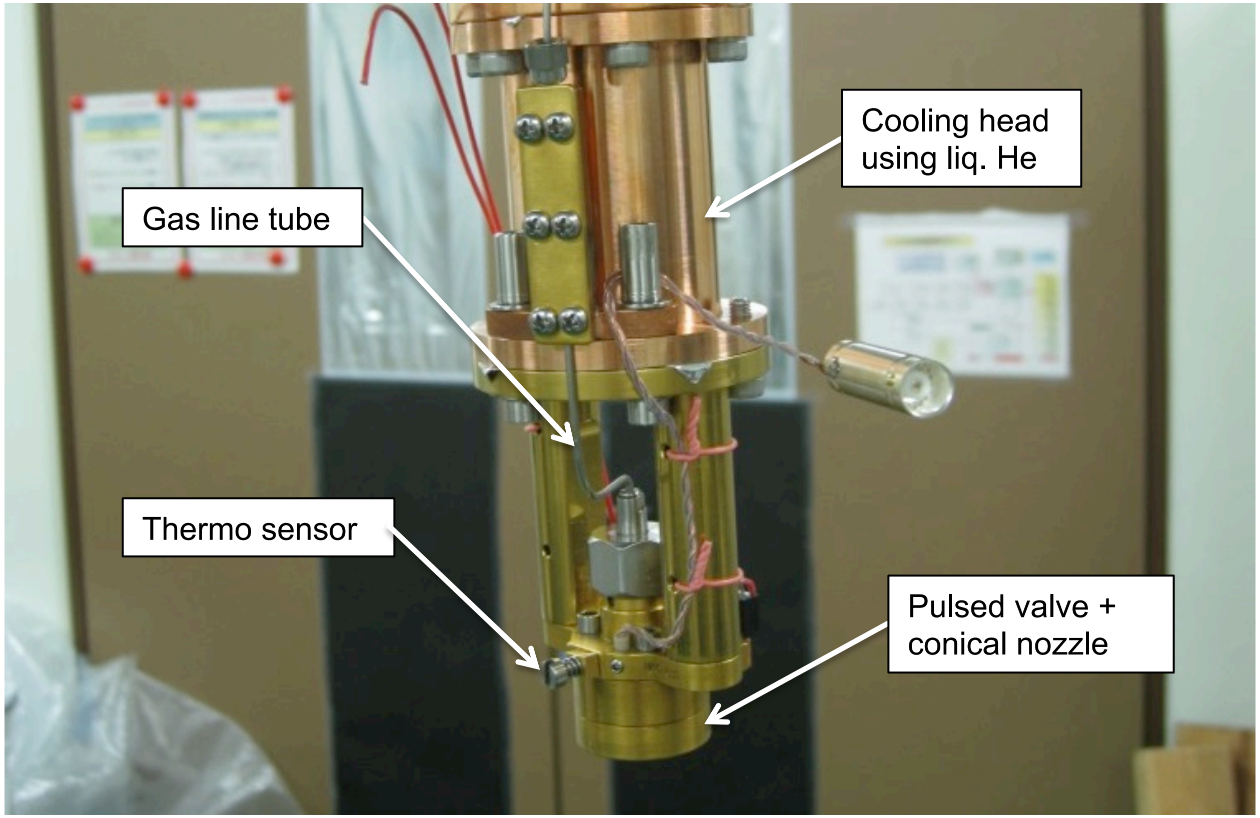
Under a major upgrading

1 PW mode (40 J, 30 fs, 0.1 Hz) coming soon…

10^{21}-10^{22} W/cm^2 could be achieved…

H. Kiriyama et al., Opt. Lett. **37**, 3363 (2012).

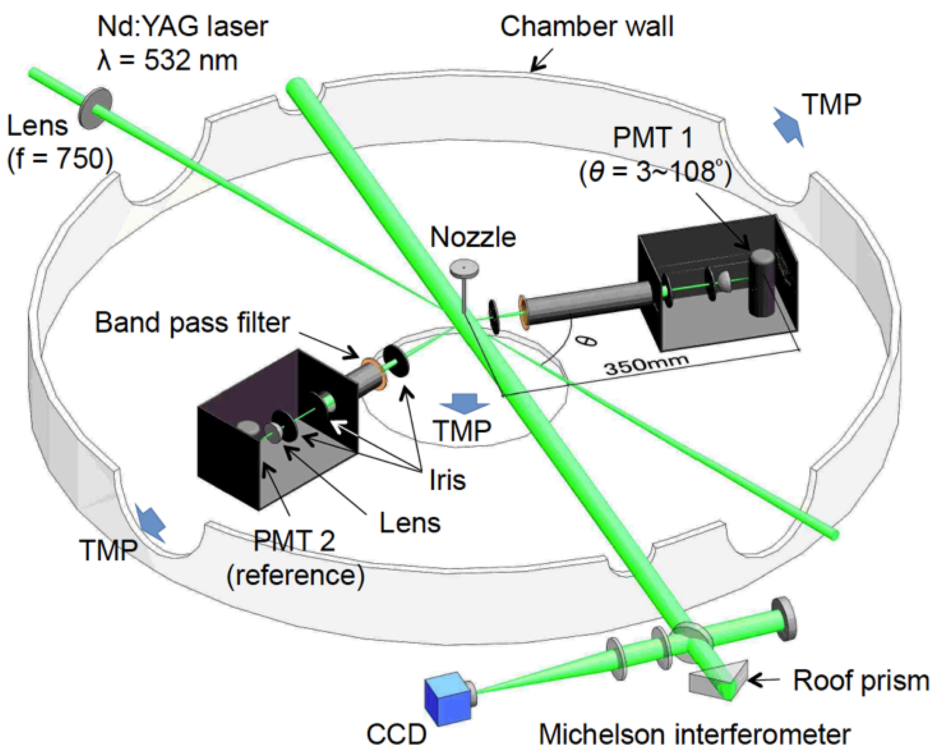
Development of submicron-size hydrogen cluster



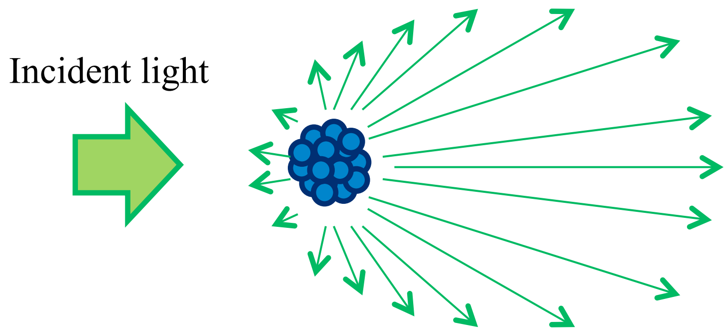
Characterization of Cluster Size using Mie scattering

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

Optical Design



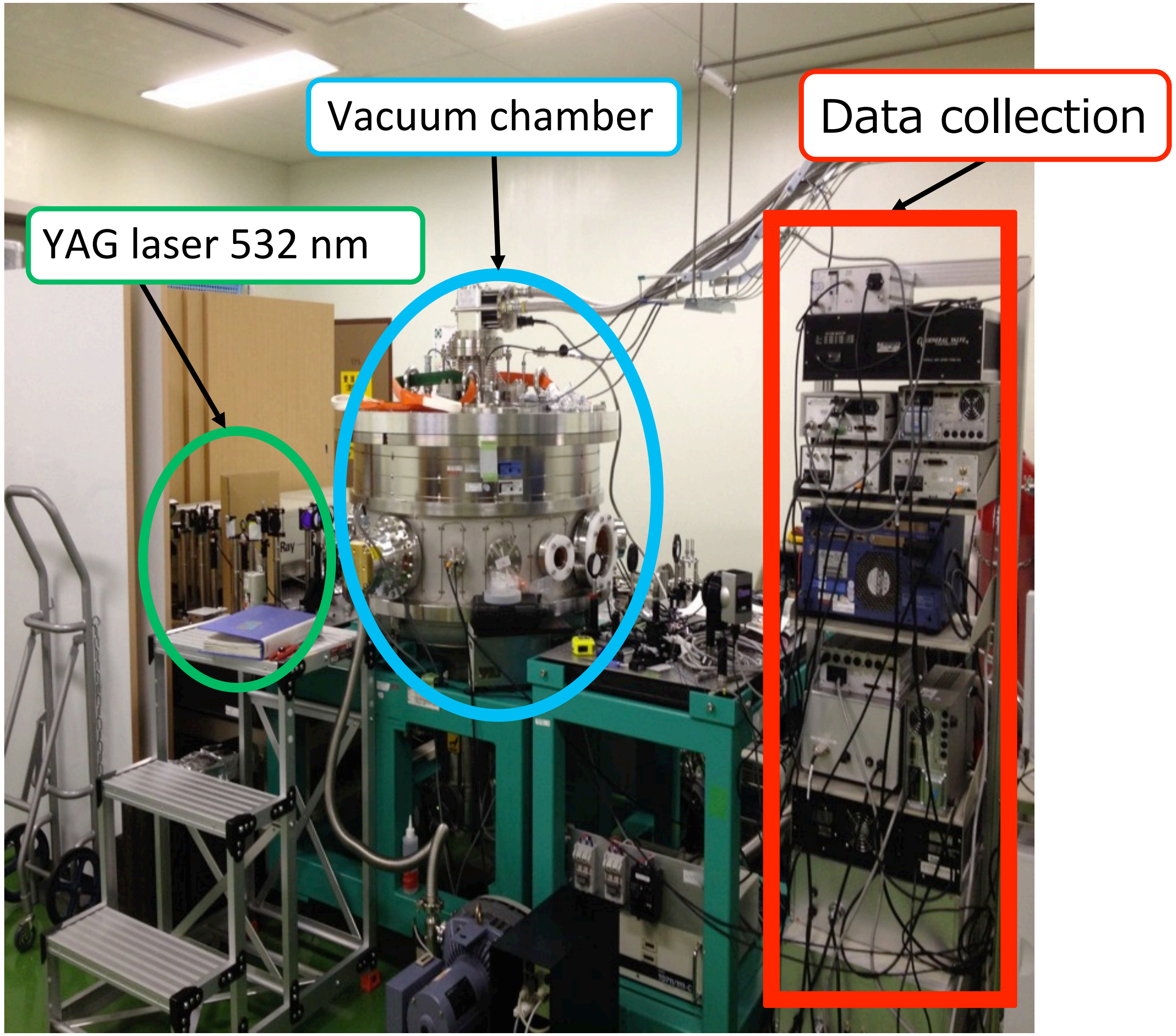
Mie Scattering



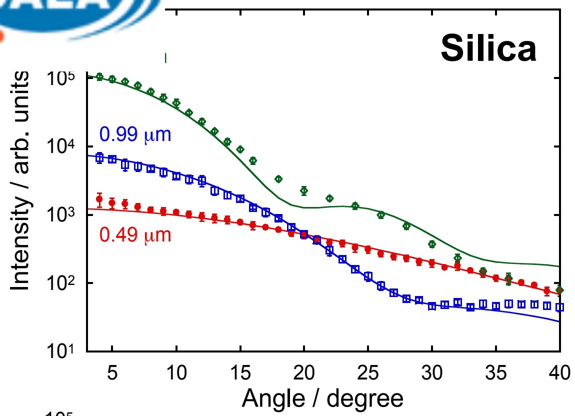
$$I(\theta) = \sum_x F(x,\theta)N(x)$$

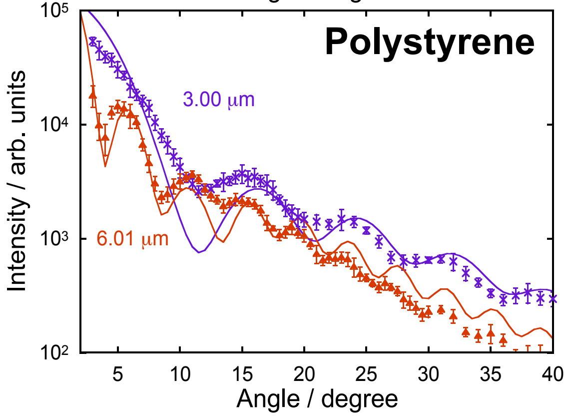
$F(x,\theta)$: Angular distribution function
$N(x)$: Size distribution function

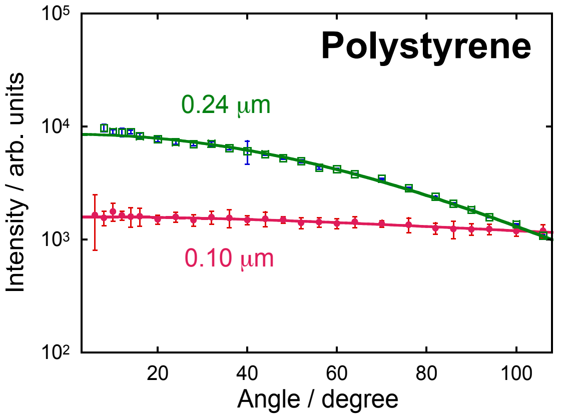
Characterization of Cluster Size using Mie scattering



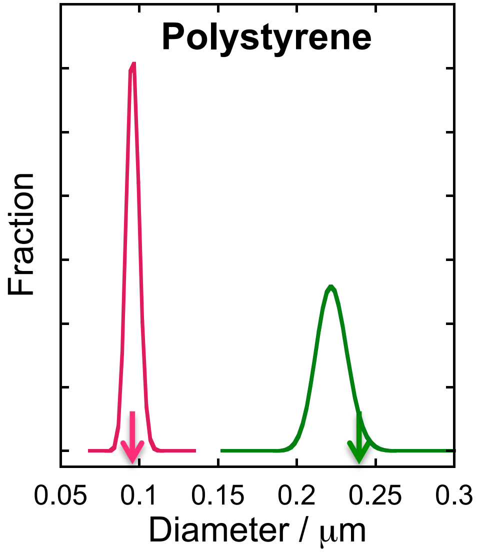
Calibration Measurements using Standard Particles

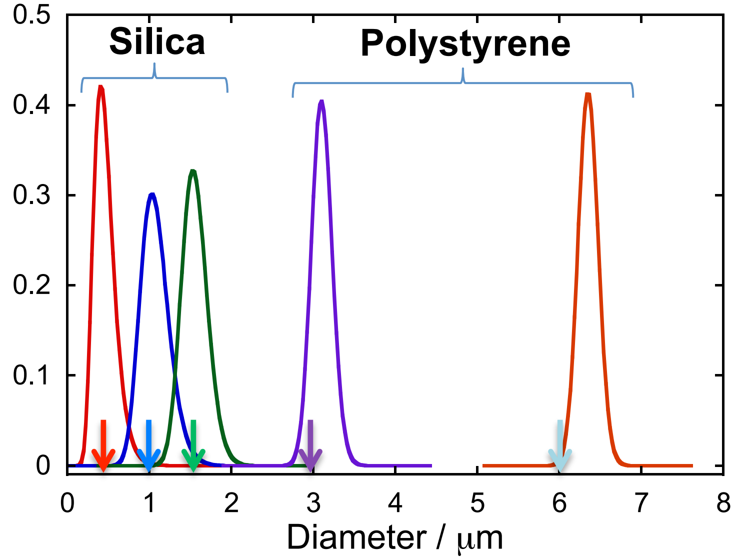






Size measurements for standard particles

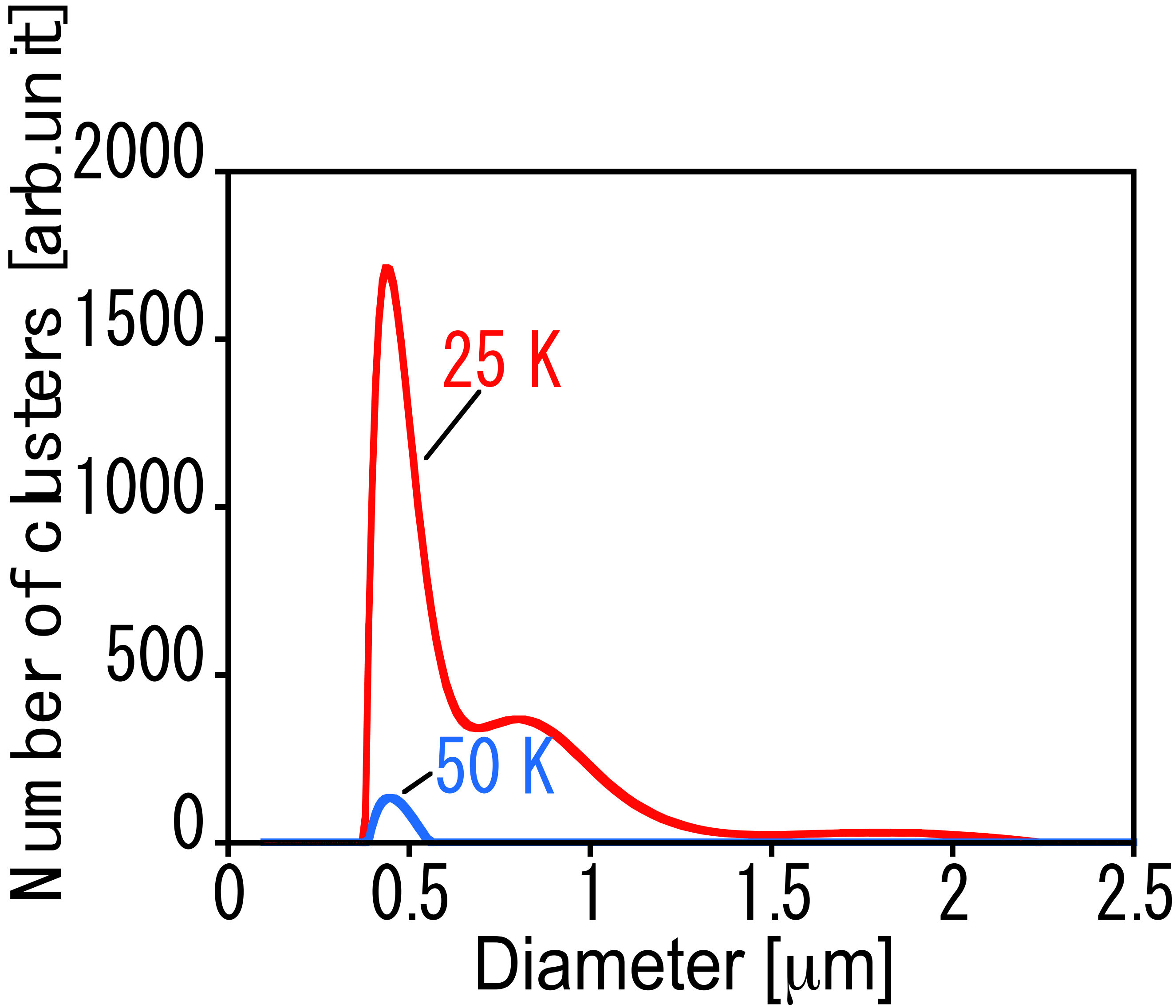




Size measurement error: < ±10%

Our system can predict particle sizes for 0.1–6 μm within 10 % error

Result: Size distributions for H_2 clusters



Summary

Development of submicron-size H_2 clusters

- Created H_2 clusters with 400-2000 nm in dia. at 25 K
- Rep. rate: up to 1 kHz!
- Debris free

2D PIC simulation for H_2 clusters (800 nm) @ 10^{22} W/cm^2

- 100 MeV class "*impurity free*" protons from PW lasers
- Anisotropic Coulomb explosion

if there is no prepulse…

need more experiments and simulations.