Nuclear Astrophysics with Lasers

A.Bonasera

Texas A&M, College Station; INFN-LNS,CATANIA

INTRODUCTION:

Create energetic ion beams under specific physical conditions, for basic nuclear science and applications.

A. Anzalone *et al*. (LAPLAFUS coll.), ***Measuring the astrophysical S-factors in plasmas***, 4th Int. Conf. on Fission properties of neutron rich nuclei. Sanibel Is. Nov. 2007. J Hamilton et al. eds. P.541.

Nuclear Astrophysics with Lasers

A.Bonasera
Texas A&M, College Station; INFN-LNS,CATANIA

INTRODUCTION:

Create energetic ion beams under specific physical conditions, for basic nuclear science and applications.

Results from U.T. (Austin, TX) experiments with petawatt laser on D+^{3}He targets (measuring the astrophysical S-factor in plasmas)

A. Anzalone *et al*. (LAPLAFUS coll.), ***Measuring the astrophysical S-factors in plasmas***, 4th Int. Conf. on Fission properties of neutron rich nuclei. Sanibel Is. Nov. 2007. J Hamilton et al. eds. P.541.

Nuclear Astrophysics with Lasers

A.Bonasera

Texas A&M, College Station; INFN-LNS,CATANIA

INTRODUCTION:

Create energetic ion beams under specific physical conditions, for basic nuclear science and applications.

Results from U.T. (Austin, TX) experiments with petawatt laser on D+^{3}He targets (measuring the astrophysical S-factor in plasmas)

Results from SGII-Shanghai experiments on CD2 targets

A. Anzalone *et al*. (LAPLAFUS coll.), ***Measuring the astrophysical S-factors in plasmas***, 4th Int. Conf. on Fission properties of neutron rich nuclei. Sanibel Is. Nov. 2007. J Hamilton et al. eds. P.541.

Nuclear Astrophysics with Lasers

A.Bonasera

Texas A&M, College Station; INFN-LNS,CATANIA

INTRODUCTION:

Create energetic ion beams under specific physical conditions, for basic nuclear science and applications.

Results from U.T. (Austin, TX) experiments with petawatt laser on D+^{3}He targets (measuring the astrophysical S-factor in plasmas)

Results from SGII-Shanghai experiments on CD2 targets

NEXT

A. Anzalone *et al*. (LAPLAFUS coll.), ***Measuring the astrophysical S-factors in plasmas***, 4th Int. Conf. on Fission properties of neutron rich nuclei. Sanibel Is. Nov. 2007. J Hamilton et al. eds. P.541.

Nuclear Astrophysics with Lasers

A.Bonasera

Texas A&M, College Station; INFN-LNS,CATANIA

INTRODUCTION:

Create energetic ion beams under specific physical conditions, for basic nuclear science and applications.

Results from U.T. (Austin, TX) experiments with petawatt laser on D+^{3}He targets (measuring the astrophysical S-factor in plasmas)

Results from SGII-Shanghai experiments on CD2 targets

NEXT

CONCLUSIONS

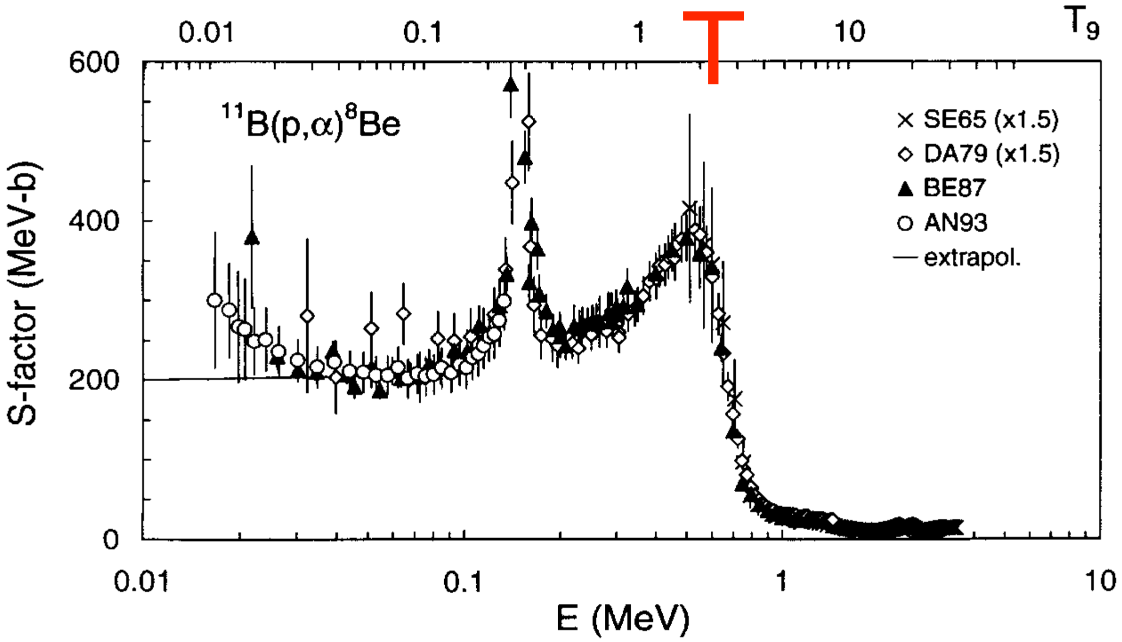
A. Anzalone *et al*. (LAPLAFUS coll.), ***Measuring the astrophysical S-factors in plasmas***, 4th Int. Conf. on Fission properties of neutron rich nuclei. Sanibel Is. Nov. 2007. J Hamilton et al. eds. P.541.

Measuring S-factors in hot and dense plasma

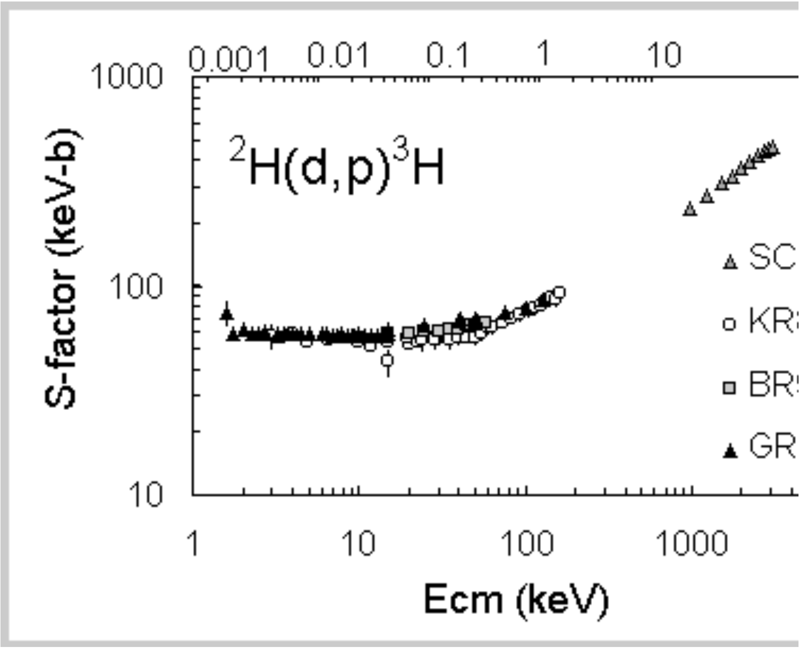
$N=\iint dV\, dt\, n_1 n_2 <\sigma_{12}\, v>$,

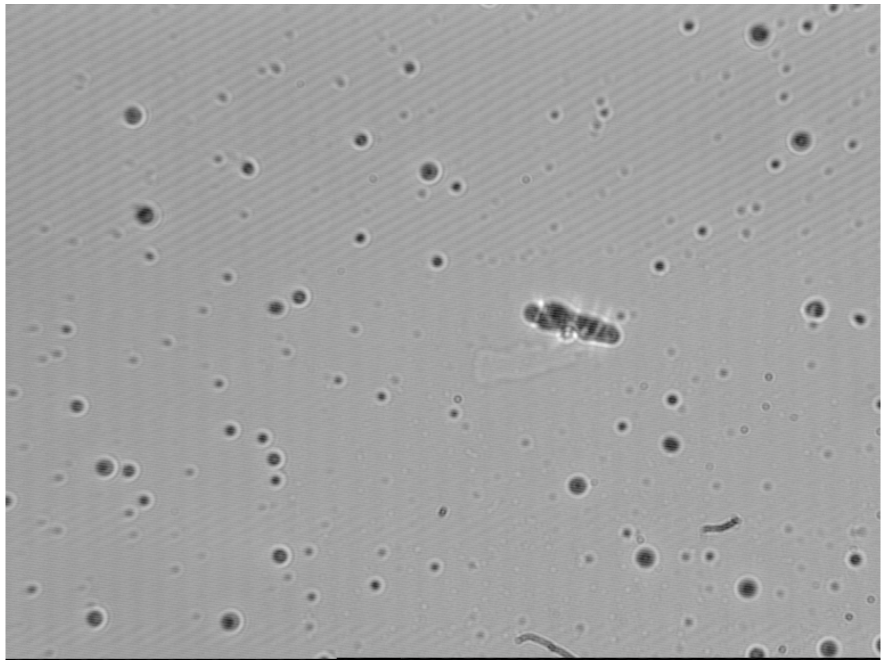
Measure the number of fusion N, the plasn phase space densities (i.e. T) n1,n2 (e.g. p+ and volumes then recover the cross-sectic (or S-factor)

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\mu\pi}} \frac{1}{(k_B T)^{3/2}} \int_0^\infty S(E) \exp\left(-\frac{E}{k_B T} - \frac{b}{\sqrt{E}}\right)$$



Add a third axis:density!





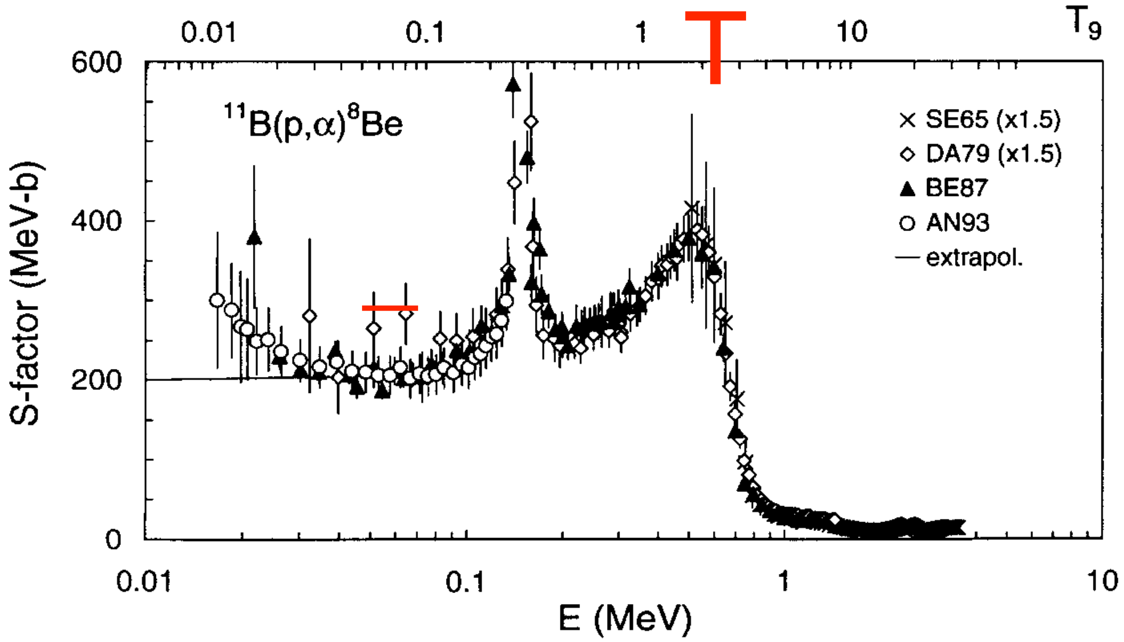
Alpha tracks from laser (p+B) interact at ABC-ENEA (LAPLAFUS coll., W.Sci. press)

Measuring S-factors in hot and dense plasma

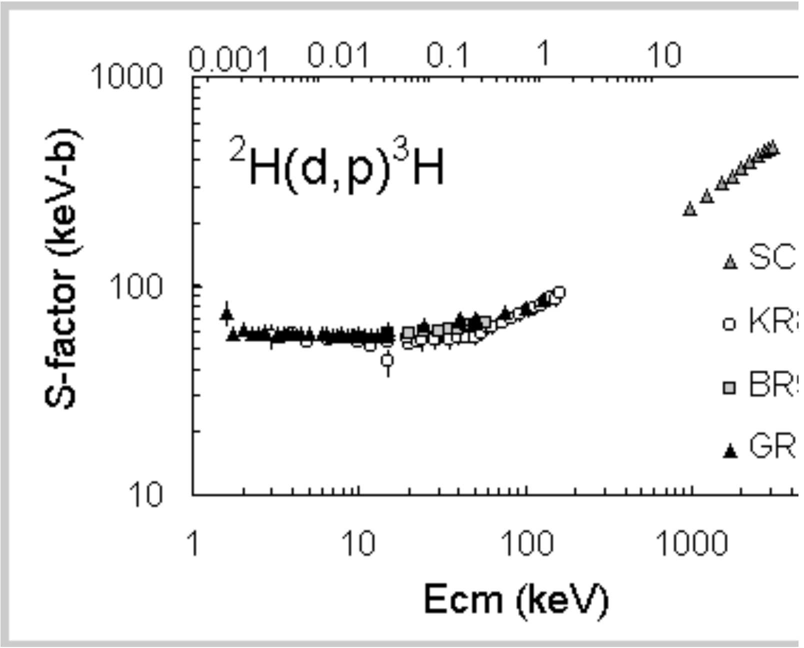
$N=\iint dV\, dt\, n_1 n_2 <\sigma_{12}\, v>,$

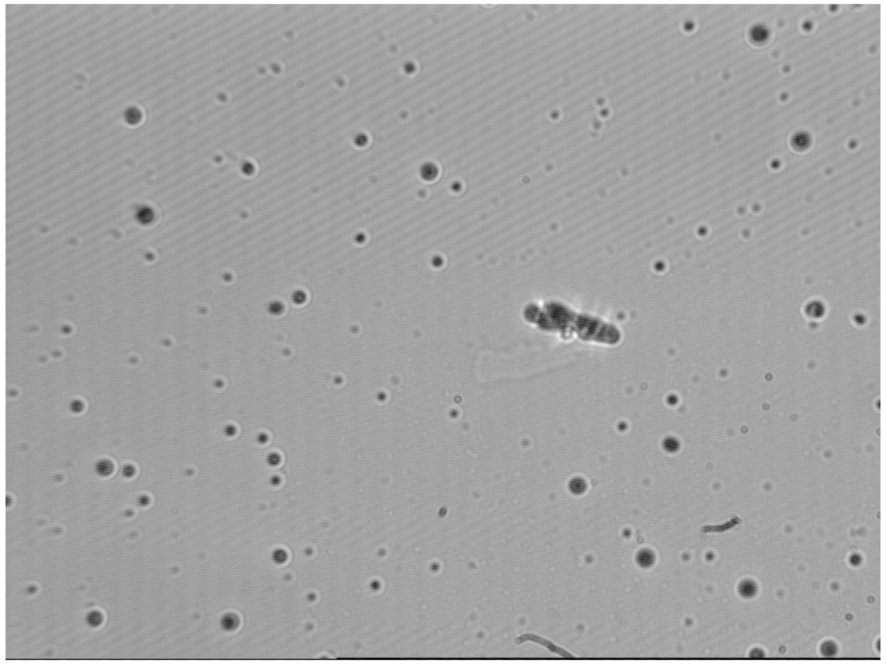
Measure the number of fusion N, the plasn phase space densities (i.e. T) n1,n2 (e.g. p+ and volumes then recover the cross-sectic (or S-factor)

$$\langle \sigma v\rangle = \sqrt{\frac{8}{\mu\pi}}\frac{1}{(k_B T)^{3/2}}\int_0^\infty S(E)\exp\left(-\frac{E}{k_B T}-\frac{b}{\sqrt{E}}\right)$$



Add a third axis:density!





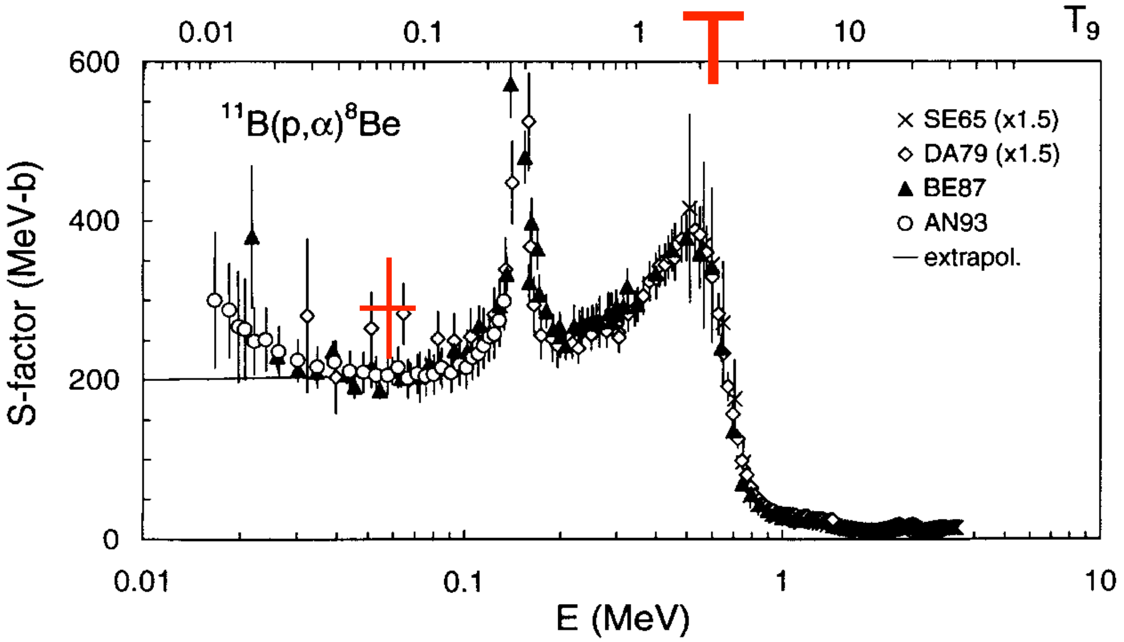
Alpha tracks from laser (p+B) interact at ABC-ENEA (LAPLAFUS coll., W.Sci. press)

Measuring S-factors in hot and dense plasma

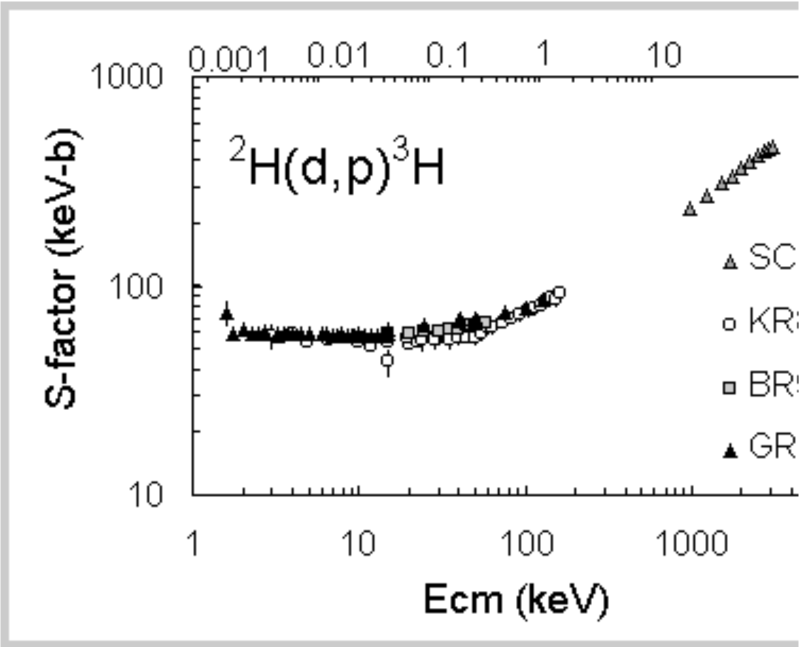
$N=\iint dV\, dt\, n_1 n_2 <\sigma_{12}\, v>$,

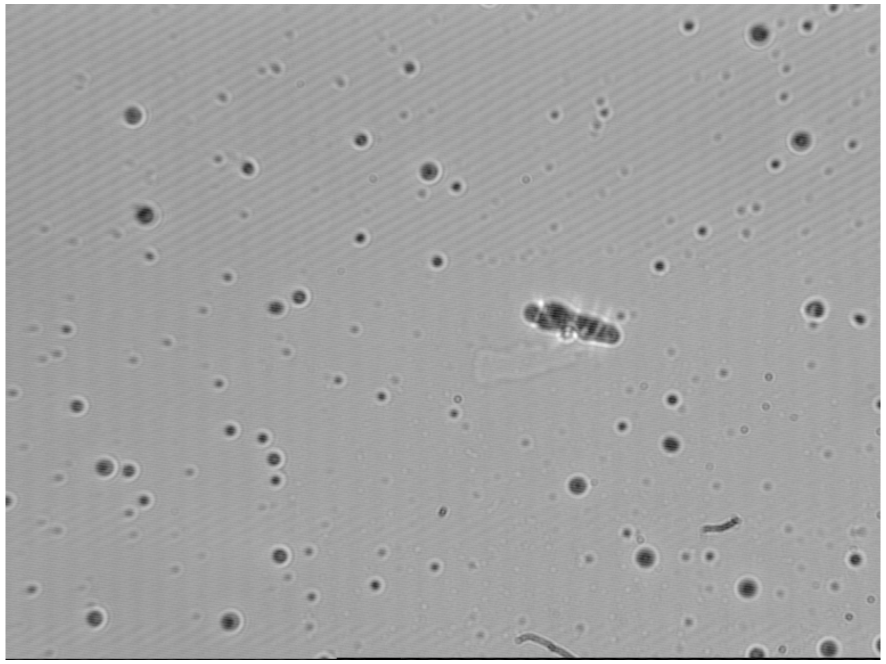
Measure the number of fusion N, the plasn
phase space densities (i.e. T) n1,n2 (e.g. p+
and volumes then recover the cross-sectic
(or S-factor)

$$\langle \sigma v\rangle = \sqrt{\frac{8}{\mu\pi}}\frac{1}{(k_BT)^{3/2}}\int_0^\infty S(E)\exp\left(-\frac{E}{k_BT}-\frac{b}{\sqrt{E}}\right)$$



Add a third axis:density!





Alpha tracks from laser (p+B) interact
at ABC-ENEA (LAPLAFUS coll., W.Sci.
press)

1.0 Title: Measuring Cluster Fusion Plasma Temperature and Density from $^{3}He(d,p)^{4}He$ and d(d,p)T Reactions

2.0 PI, Co-PI's & Affiliation

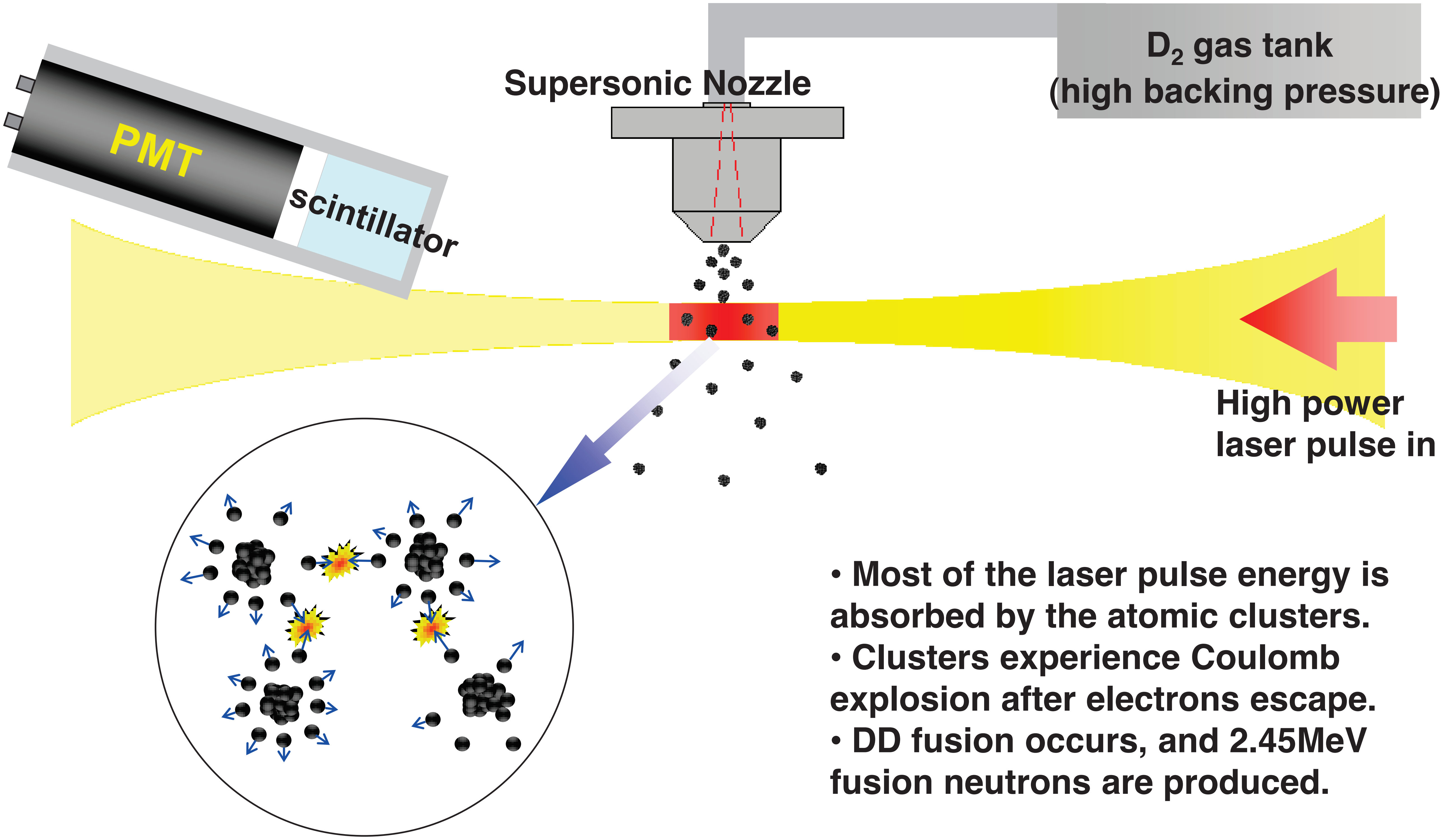
PIs: Todd Ditmire (UT Austin), Aldo Bonasera (Texas A&M, LNS INFN Catania-Italy)
Co-investigators: W. Bang, G. Dyer, H. Quevedo, A. Bernstein (CHEDS, UT Austin)
M. Barbui, M. Barbarino, G. Giuliani, K. Hagel, Z. Hua, J. Natowitz, K. Schmidt (Cyclotron Institute, Texas A&M University, College Station, TX)
A. Caruso (Kore University, Enna-Italy)
J. Sura (Heavy Ion Institute, Warsaw, Poland)
S. Kimura (LNS INFN Catania-Italy)
P.Andreoli, R.DeAngelis, F.Consoli, ENEA

3.0 Experimental Objectives and Concept

We propose to conduct experiments that follow on from the successful deuterium cluster fusion experiments in early 2011 on the TPW. Specifically we propose a detailed investigation of ion temperature in hot exploding cluster plasmas. To do this we will simultaneously measure the experimental yield from two different nuclear reactions. While our first experiments utilized pure deuterium to drive the d(d,p)T and $d(d,n)He^{3}$ reactions we now propose to mix He^{3} into the gas jet target to allow us to measure simultaneously yields from the $He^{3}(d,p)He^{4}$ and the d-d reactions. Because these two reactions have different cross sections, measuring the ratio of the yields between these two reactions will allow a precise determination of the plasma temperature at the time when the reaction occurred (assuming thermalization). The measure of the experimental yield from sequential reactions will also make possible a direct measurement of the plasma density at the time of the reaction. Once the

High power laser can be used to generate neutrons from the fusion reaction

Nuclear fusion from laser-cluster interaction



- Most of the laser pulse energy is absorbed by the atomic clusters.
- Clusters experience Coulomb explosion after electrons escape.
- DD fusion occurs, and 2.45MeV fusion neutrons are produced.

Expected fusion reactions:

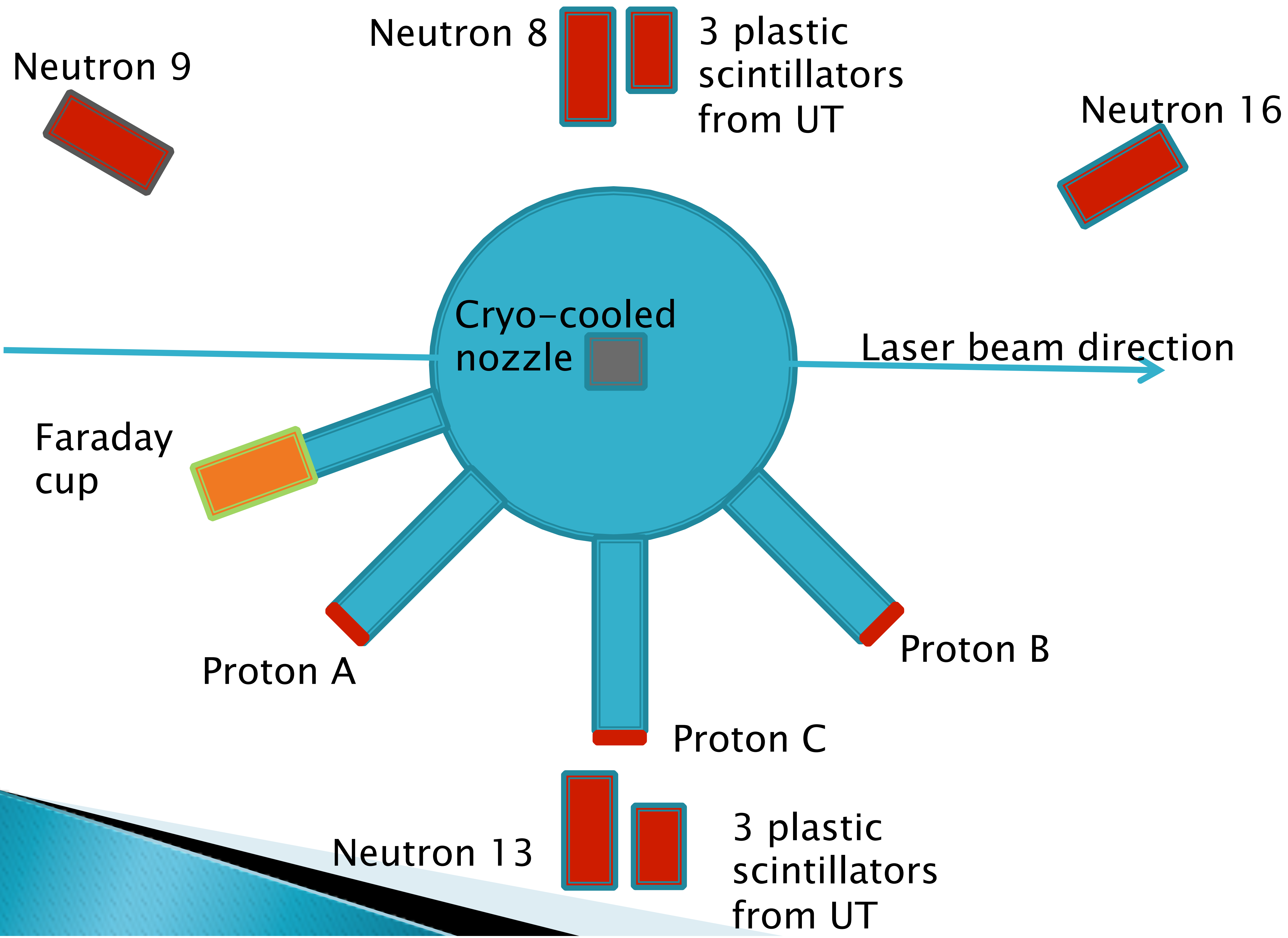
D + D ->T (1.01 MeV) + p (3.02 MeV) (50%)

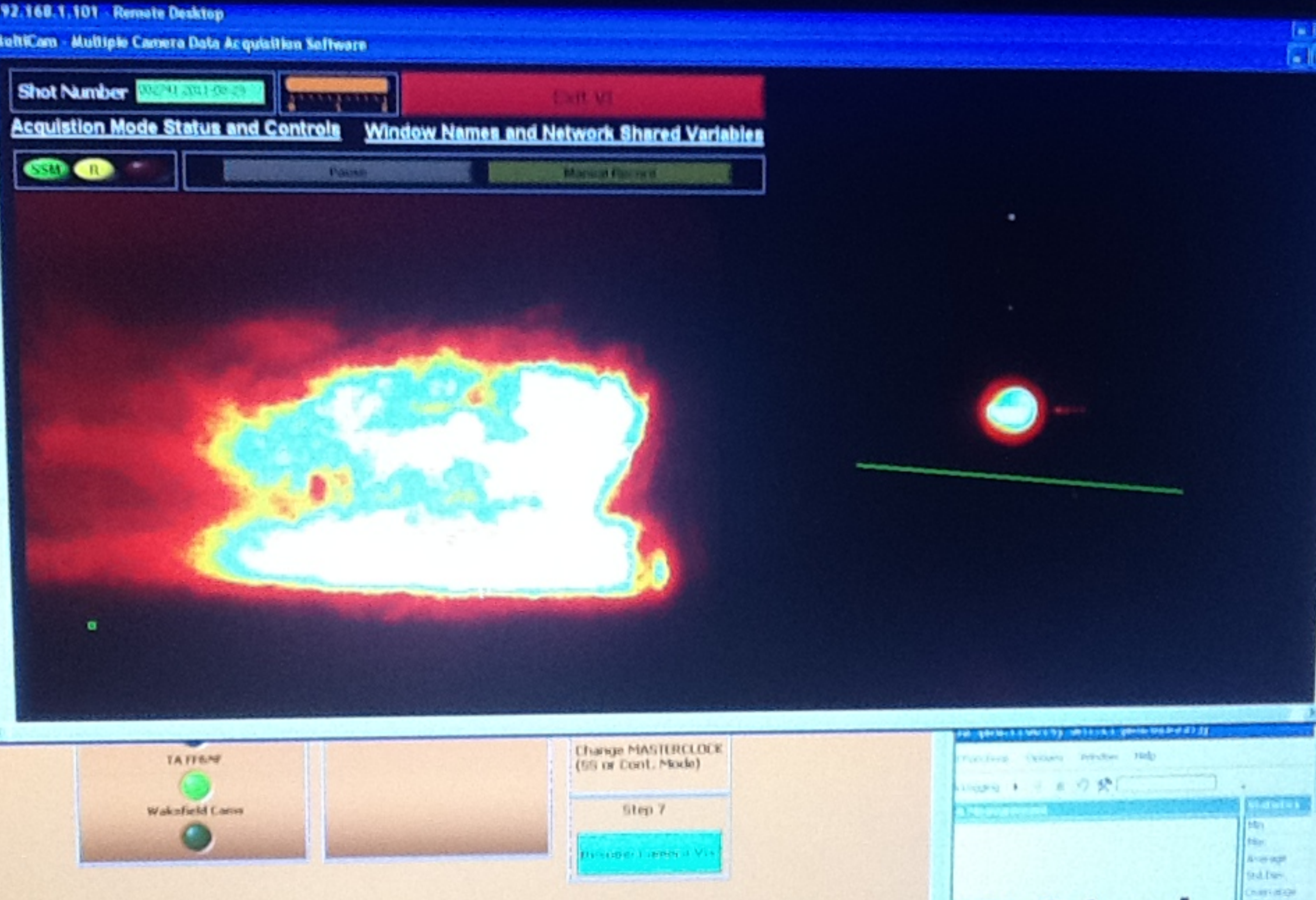
D + D -> ^{3}He (0.82 MeV) + n (2.45 MeV) (50%)

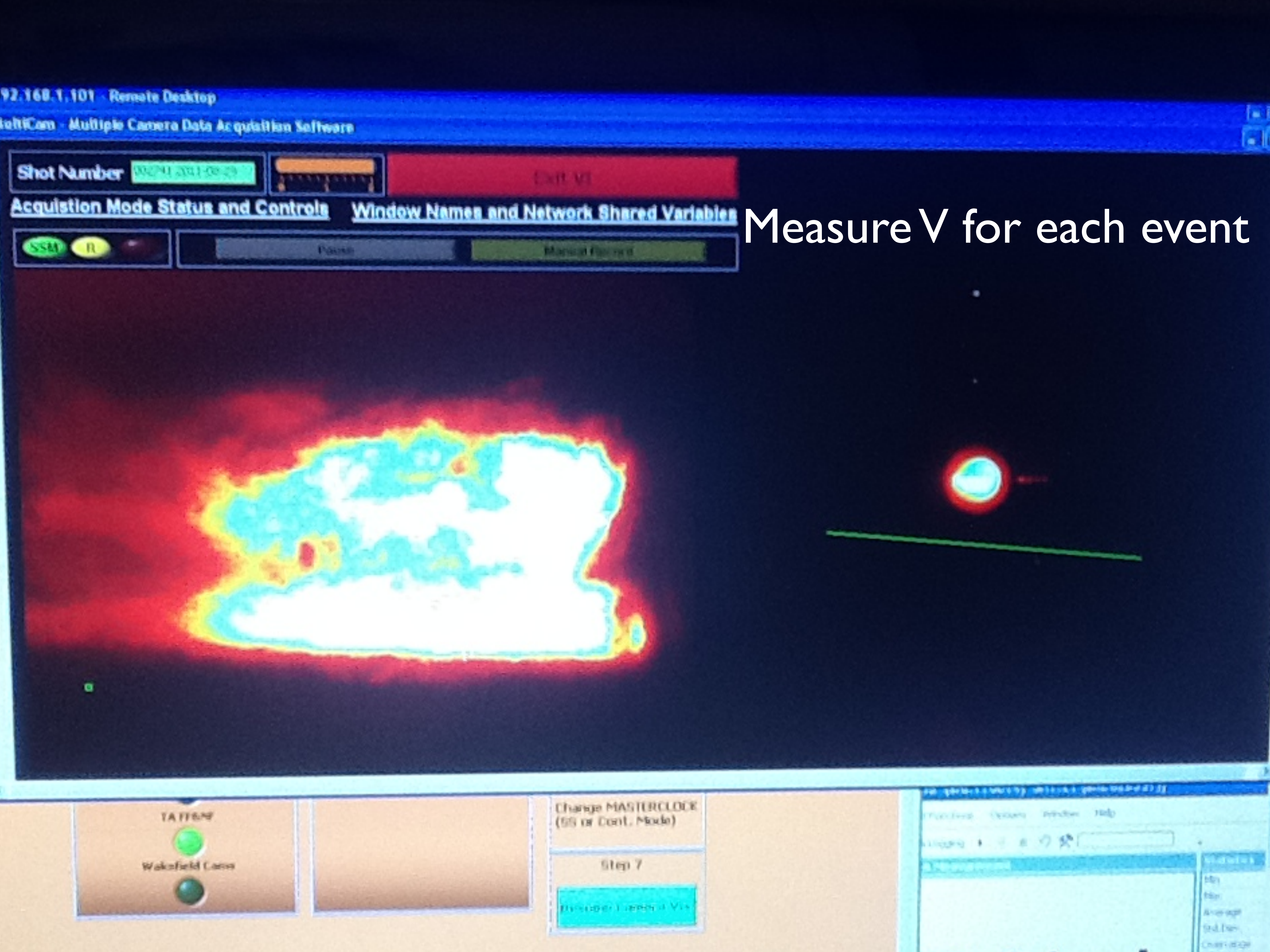
D + ^{3}He-> ^{4}He (3.6 MeV) + p (14.69 MeV) (100%)

D + T-> ^{4}He (3.5 MeV) + n (14.1 MeV) (100%)

Experimental setup




92.168.1.101 - Remote Desktop
ultiCam - Multiple Camera Data Acquisition Software
Shot Number
Exit VI
Acquistion Mode Status and Controls
Window Names and Network Shared Variables
SSM
R
Pause
Manual Record
TA FF&NF
Wakefield Cams
Change MASTERCLOCK
(SS or Cont. Mode)
Step 7
Options
Window
Help
Min
Max
Average
Std Dev

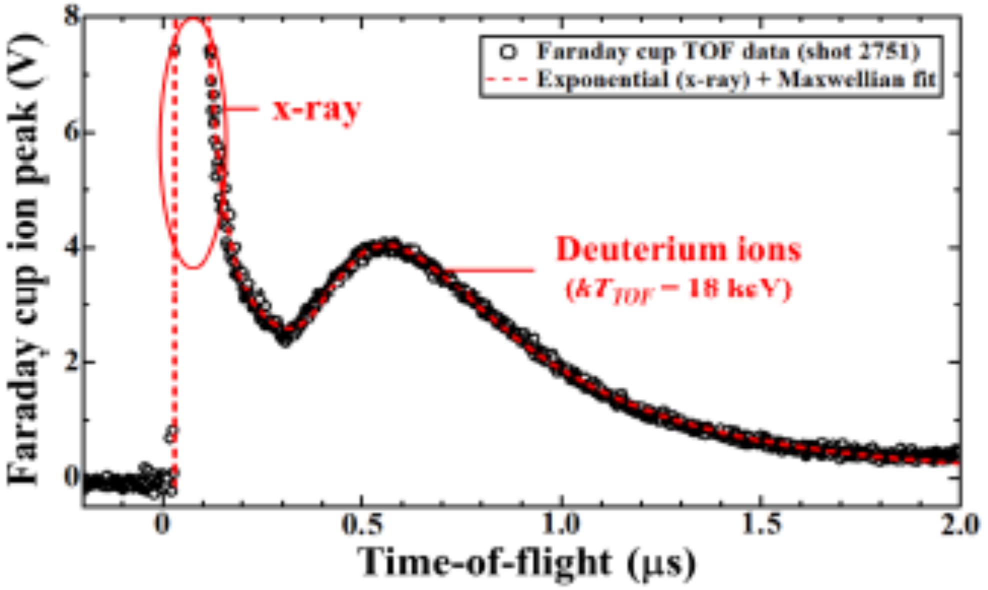


Measure V for each event

Measured observables

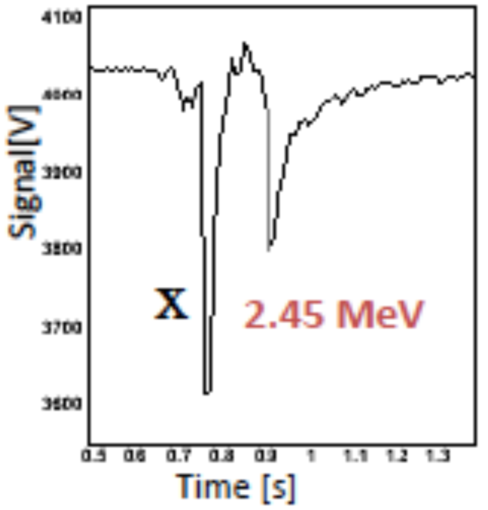
Temperature and the number of the energetic ions

Faraday cup



Yield of 2.45 MeV neutrons

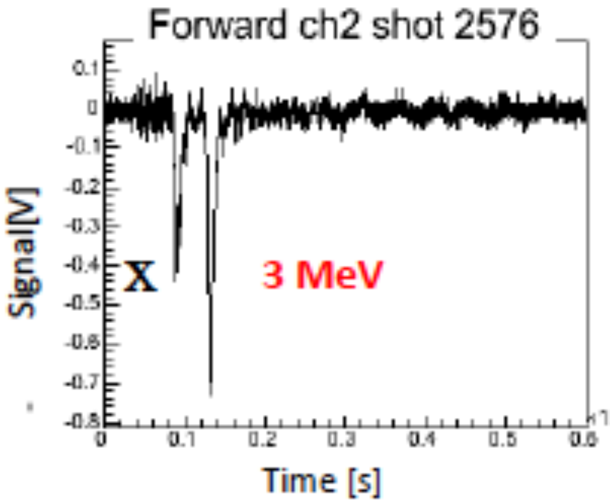
4 liquid scintillators NE213 placed at different angles and 6 plastic scintillators placed at 90 degrees

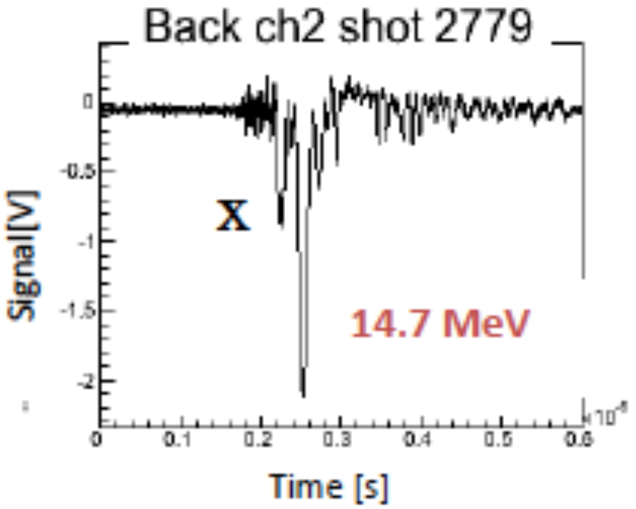


Yield of 3.02 MeV protons

Yield of 14.7 MeV protons

Thin (254 um) plastic scintillators BC400.



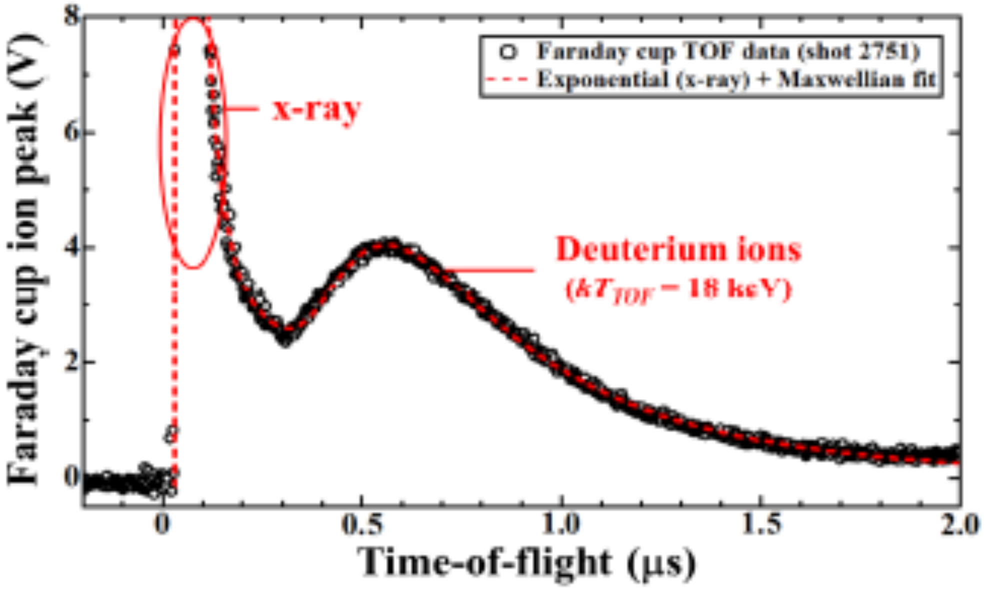


Measured observables

Measure N. of ions

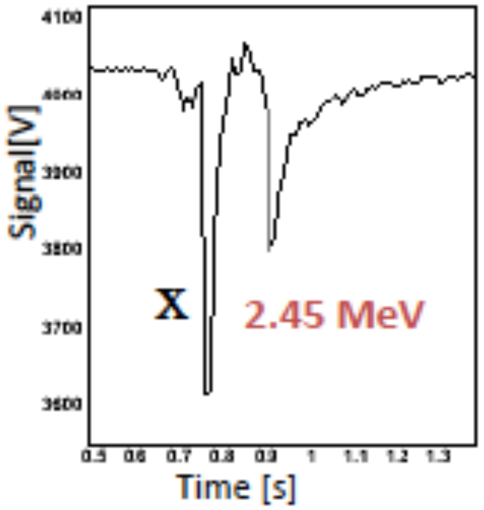
Temperature and the number of the energetic ions

Faraday cup



Yield of 2.45 MeV neutrons

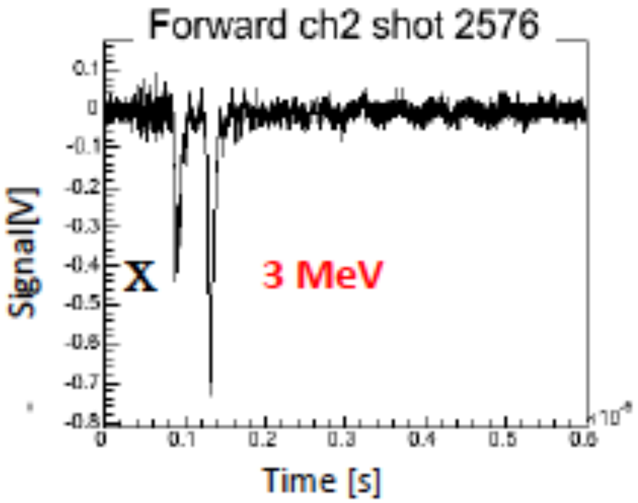
4 liquid scintillators NE213 placed at different angles and 6 plastic scintillators placed at 90 degrees

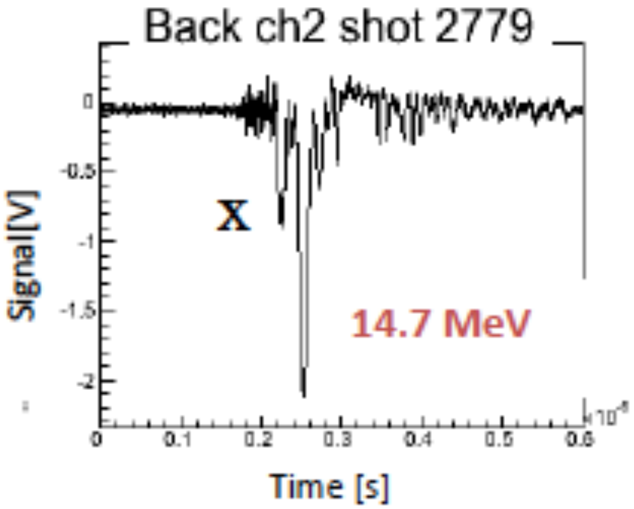


Yield of 3.02 MeV protons

Yield of 14.7 MeV protons

Thin (254 um) plastic scintillators BC400.



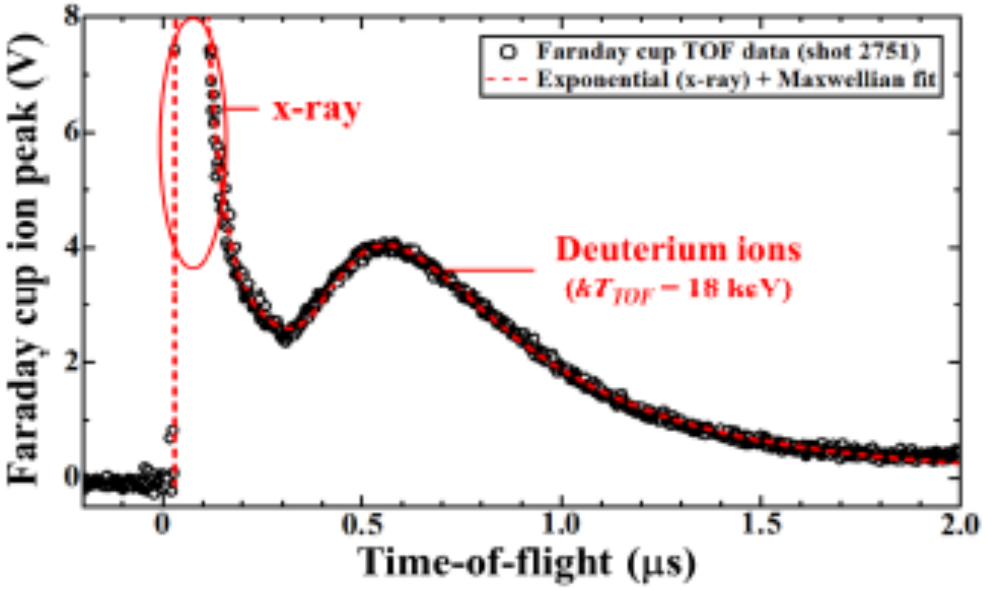


Measured observables

Measure N. of ions

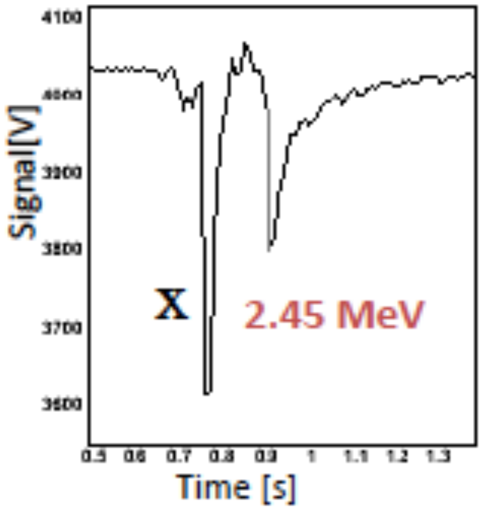
Temperature and the number of the energetic ions

Faraday cup



Yield of 2.45 MeV neutrons

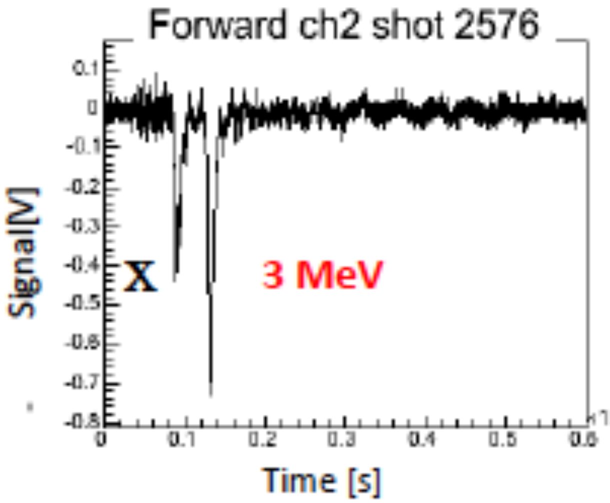
4 liquid scintillators NE213 placed at different angles and 6 plastic scintillators placed at 90 degrees

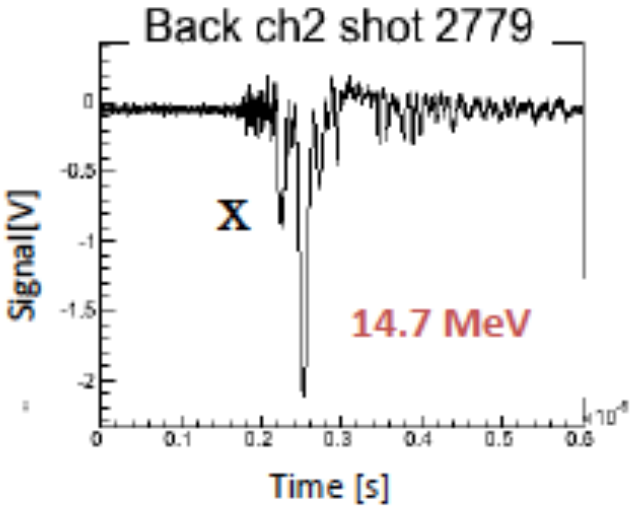


Yield of 3.02 MeV protons

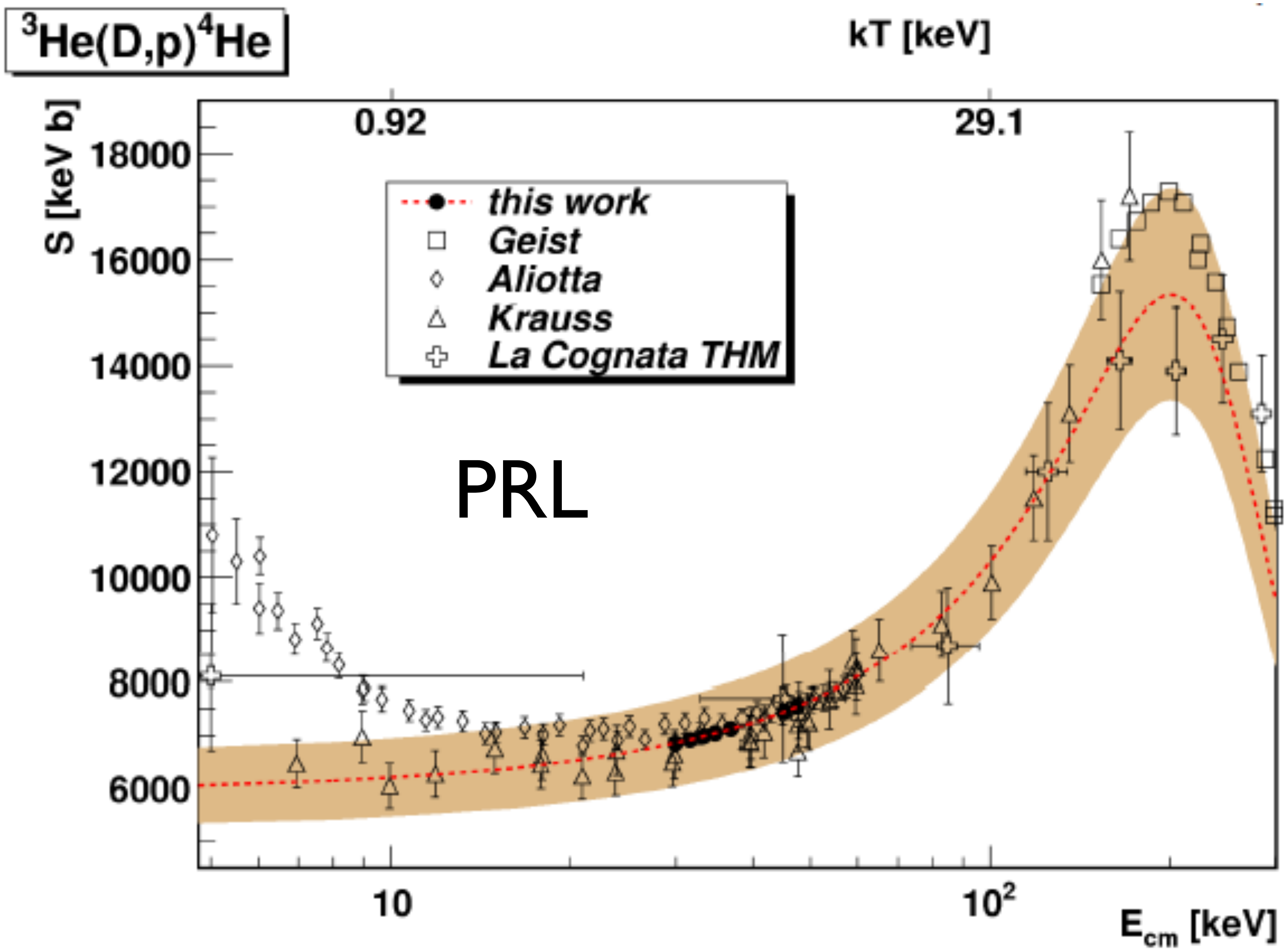
Yield of 14.7 MeV protons

Thin (254 um) plastic scintillators BC400.



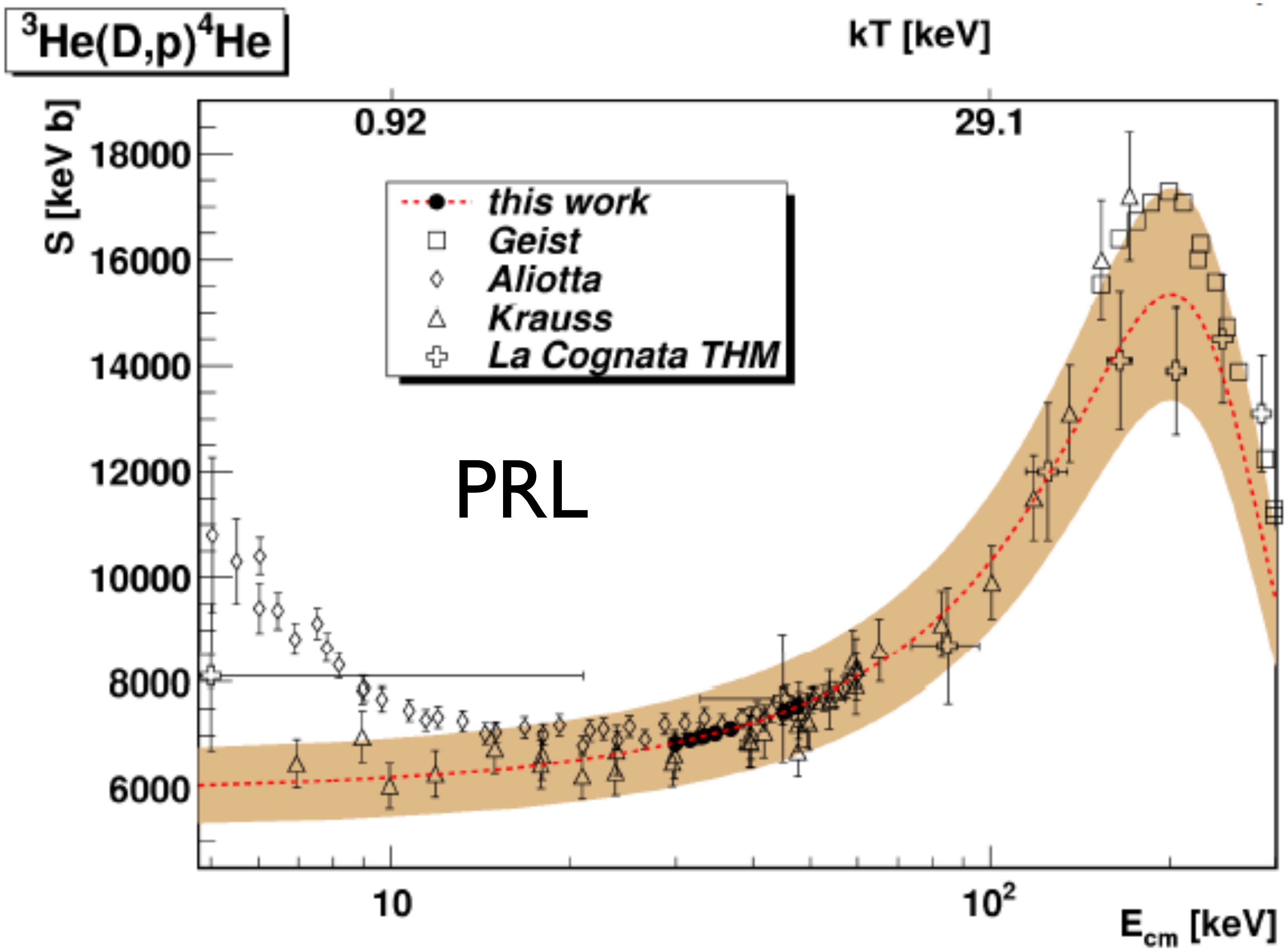


Measure N.of fusions for each channel

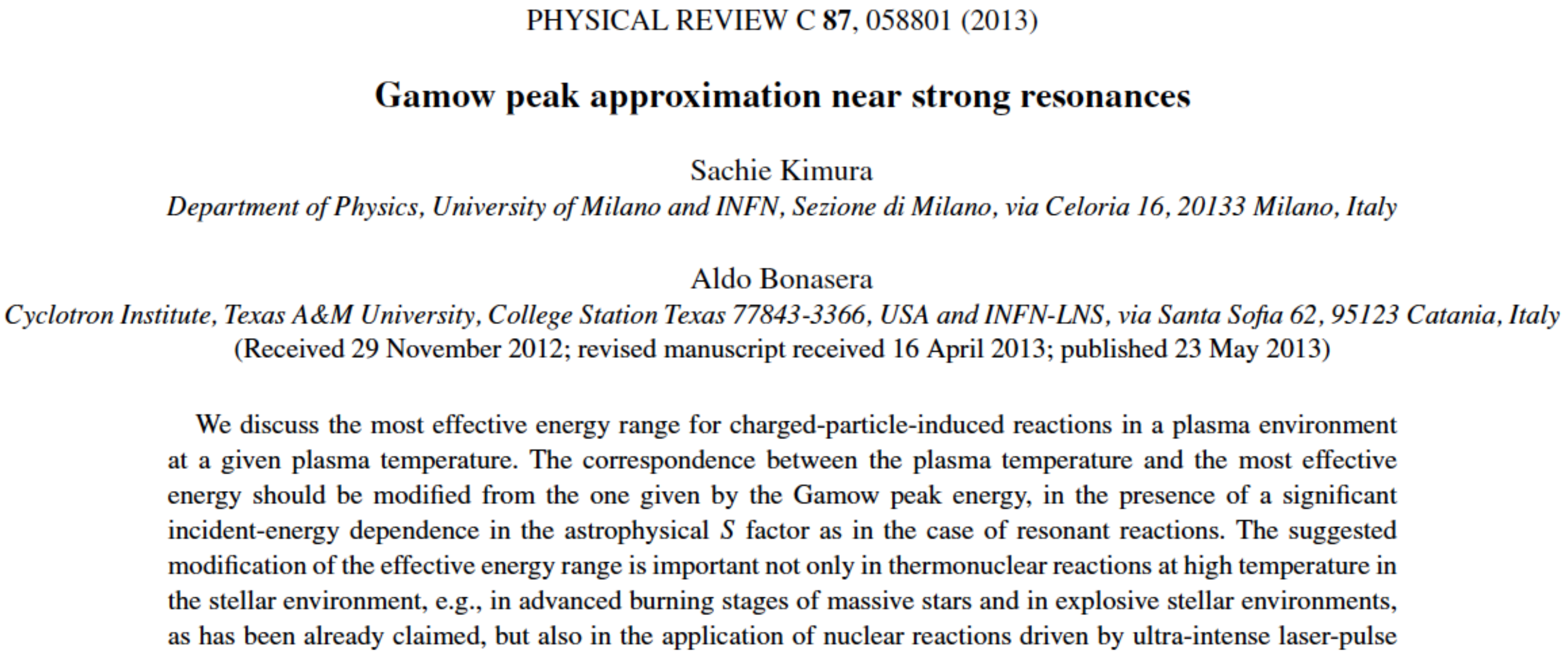


$^3He(D,p)^4He$
kT [keV]
0.92
29.1
S [keV b]
18000
16000
14000
12000
10000
8000
6000
this work
Geist
Aliotta
Krauss
La Cognata THM
10
10^2
E_{cm} [keV]

PRL



PRL



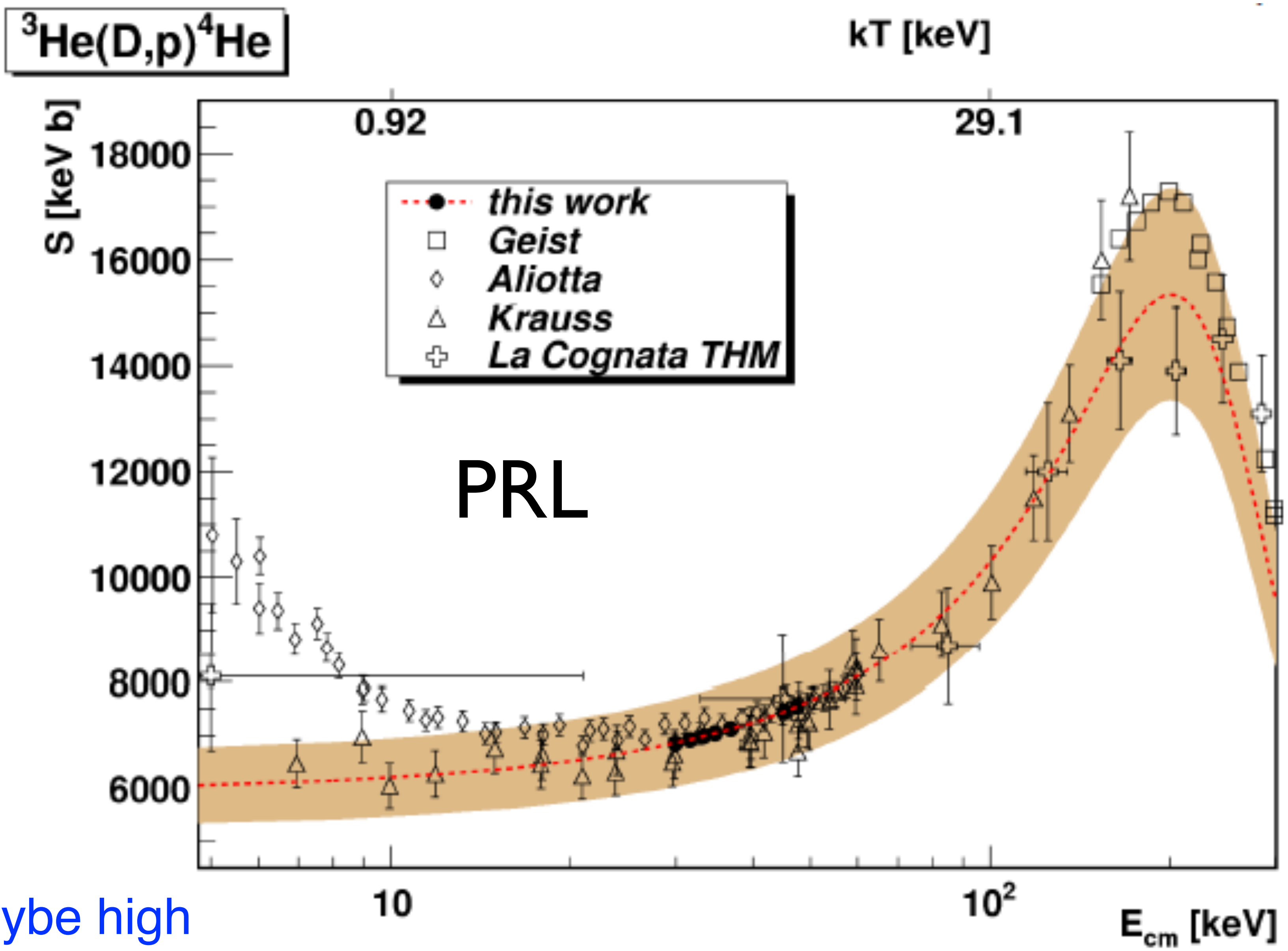
PHYSICAL REVIEW C **87**, 058801 (2013)

Gamow peak approximation near strong resonances

Sachie Kimura
Department of Physics, University of Milano and INFN, Sezione di Milano, via Celoria 16, 20133 Milano, Italy

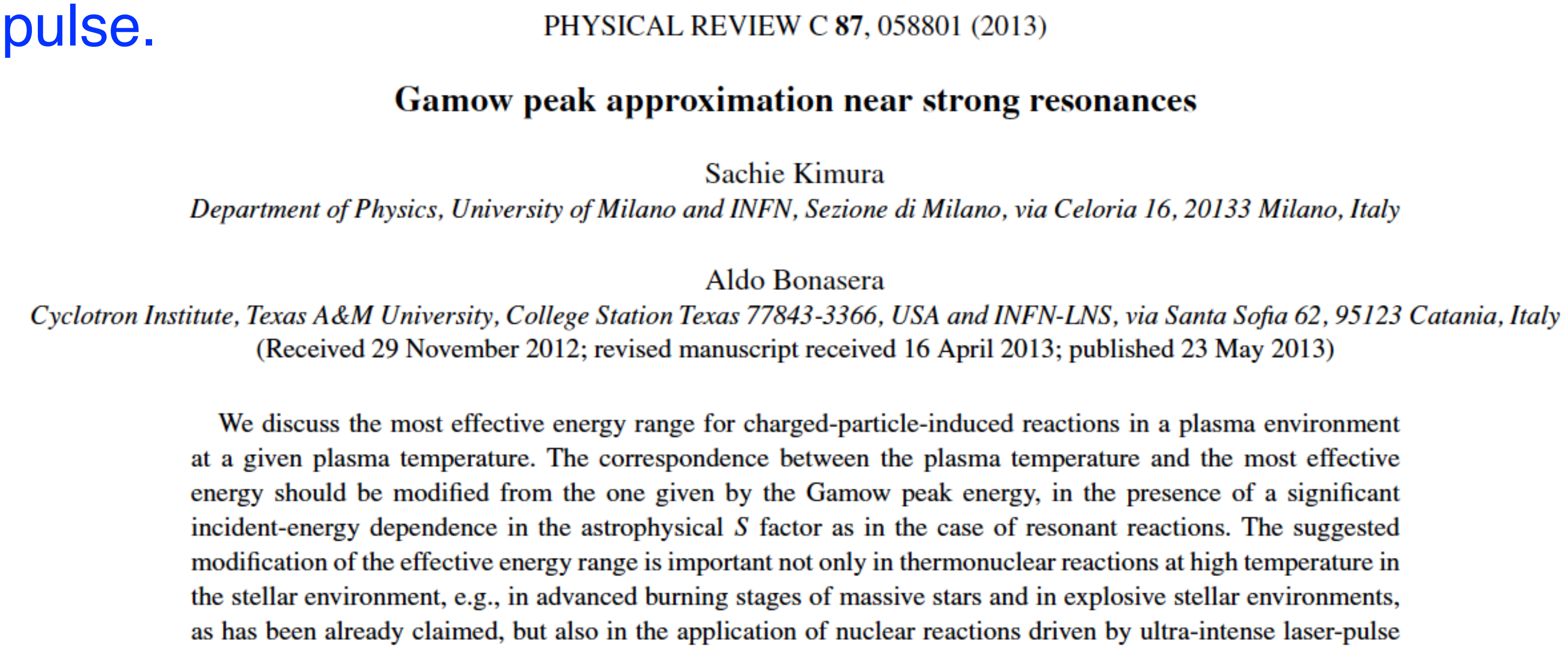
Aldo Bonasera
Cyclotron Institute, Texas A&M University, College Station Texas 77843-3366, USA and INFN-LNS, via Santa Sofia 62, 95123 Catania, Italy
(Received 29 November 2012; revised manuscript received 16 April 2013; published 23 May 2013)

We discuss the most effective energy range for charged-particle-induced reactions in a plasma environment at a given plasma temperature. The correspondence between the plasma temperature and the most effective energy should be modified from the one given by the Gamow peak energy, in the presence of a significant incident-energy dependence in the astrophysical *S* factor as in the case of resonant reactions. The suggested modification of the effective energy range is important not only in thermonuclear reactions at high temperature in the stellar environment, e.g., in advanced burning stages of massive stars and in explosive stellar environments, as has been already claimed, but also in the application of nuclear reactions driven by ultra-intense laser-pulse



PRL

Here maybe high repetition laser low energy fs pulse.



PHYSICAL REVIEW C **87**, 058801 (2013)

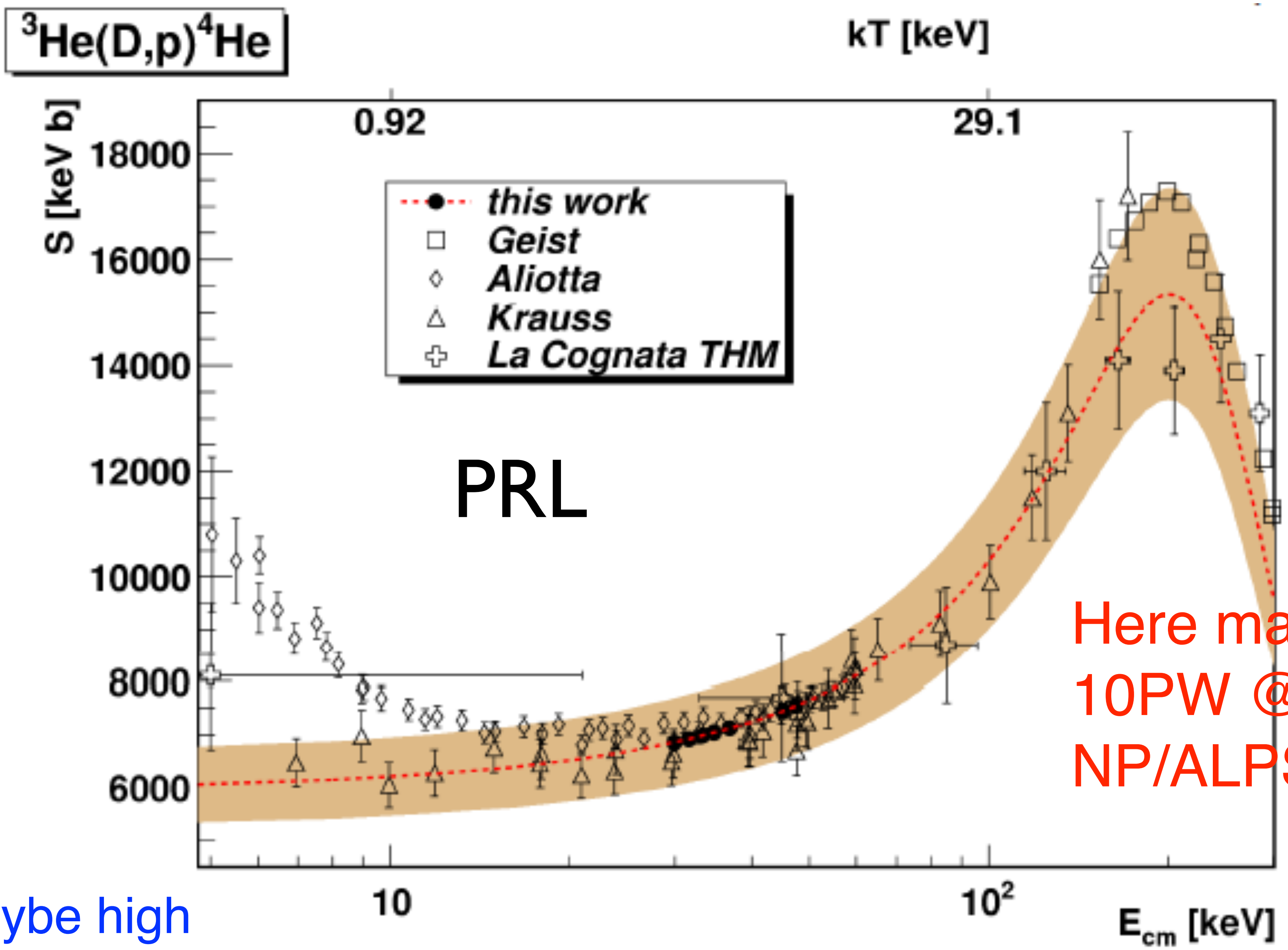
Gamow peak approximation near strong resonances

Sachie Kimura
Department of Physics, University of Milano and INFN, Sezione di Milano, via Celoria 16, 20133 Milano, Italy

Aldo Bonasera
Cyclotron Institute, Texas A&M University, College Station Texas 77843-3366, USA and INFN-LNS, via Santa Sofia 62, 95123 Catania, Italy

(Received 29 November 2012; revised manuscript received 16 April 2013; published 23 May 2013)

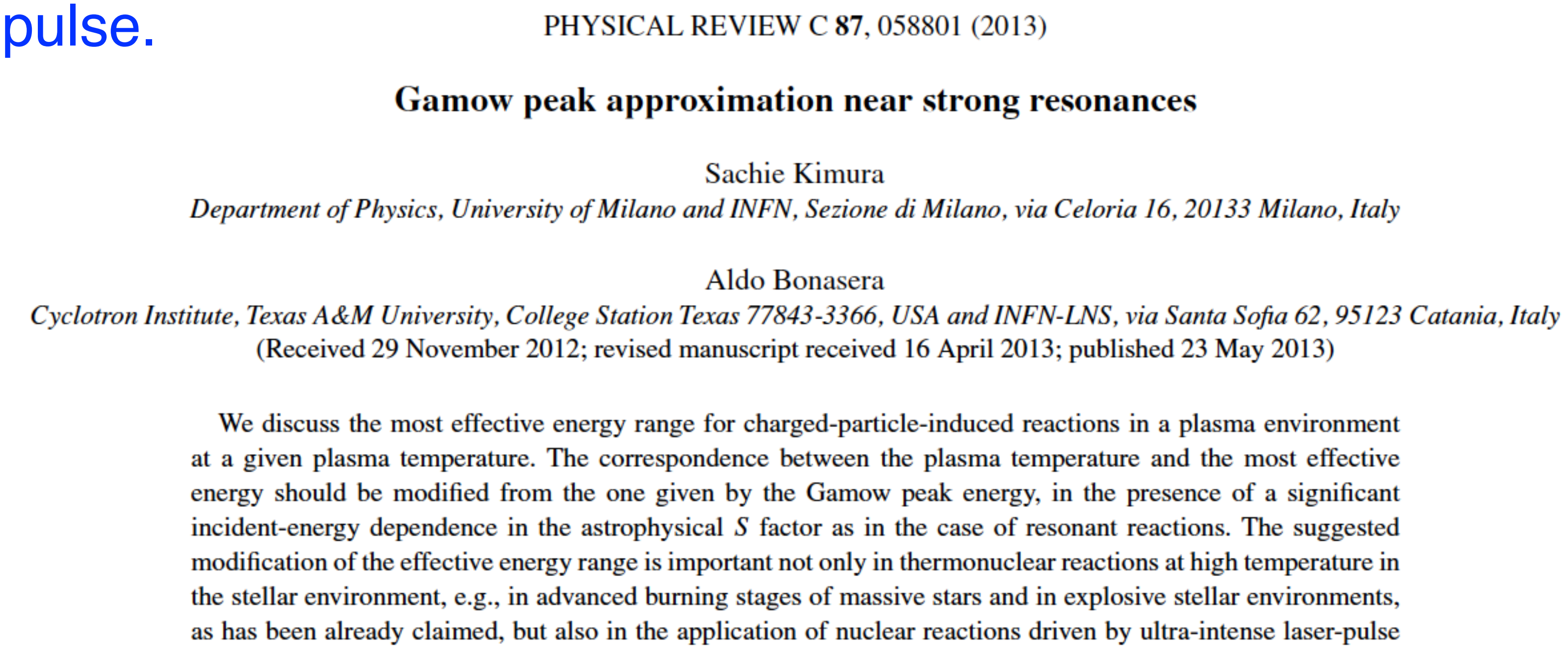
We discuss the most effective energy range for charged-particle-induced reactions in a plasma environment at a given plasma temperature. The correspondence between the plasma temperature and the most effective energy should be modified from the one given by the Gamow peak energy, in the presence of a significant incident-energy dependence in the astrophysical S factor as in the case of resonant reactions. The suggested modification of the effective energy range is important not only in thermonuclear reactions at high temperature in the stellar environment, e.g., in advanced burning stages of massive stars and in explosive stellar environments, as has been already claimed, but also in the application of nuclear reactions driven by ultra-intense laser-pulse



PRL

Here maybe the 10PW @ELI-NP/ALPS/MED

Here maybe high repetition laser low energy fs pulse.



PHYSICAL REVIEW C **87**, 058801 (2013)

Gamow peak approximation near strong resonances

Sachie Kimura
Department of Physics, University of Milano and INFN, Sezione di Milano, via Celoria 16, 20133 Milano, Italy

Aldo Bonasera
Cyclotron Institute, Texas A&M University, College Station Texas 77843-3366, USA and INFN-LNS, via Santa Sofia 62, 95123 Catania, Italy
(Received 29 November 2012; revised manuscript received 16 April 2013; published 23 May 2013)

We discuss the most effective energy range for charged-particle-induced reactions in a plasma environment at a given plasma temperature. The correspondence between the plasma temperature and the most effective energy should be modified from the one given by the Gamow peak energy, in the presence of a significant incident-energy dependence in the astrophysical S factor as in the case of resonant reactions. The suggested modification of the effective energy range is important not only in thermonuclear reactions at high temperature in the stellar environment, e.g., in advanced burning stages of massive stars and in explosive stellar environments, as has been already claimed, but also in the application of nuclear reactions driven by ultra-intense laser-pulse

PRL **111,** 055002 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

Temperature Measurements of Fusion Plasmas Produced by Petawatt-Laser-Irradiated $D_2 - {}^3He$ or $CD_4 - {}^3He$ Clustering Gases

W. Bang,[1,*] M. Barbui,[2] A. Bonasera,[2,3] G. Dyer,[1] H. J. Quevedo,[1] K. Hagel,[2] K. Schmidt,[2] F. Consoli,[4]
R. De Angelis,[4] P. Andreoli,[4] E. Gaul,[1] A. C. Bernstein,[1] M. Donovan,[1] M. Barbarino,[2] S. Kimura,[3]
M. Mazzocco,[5] J. Sura,[6] J. B. Natowitz,[2] and T. Ditmire[1]

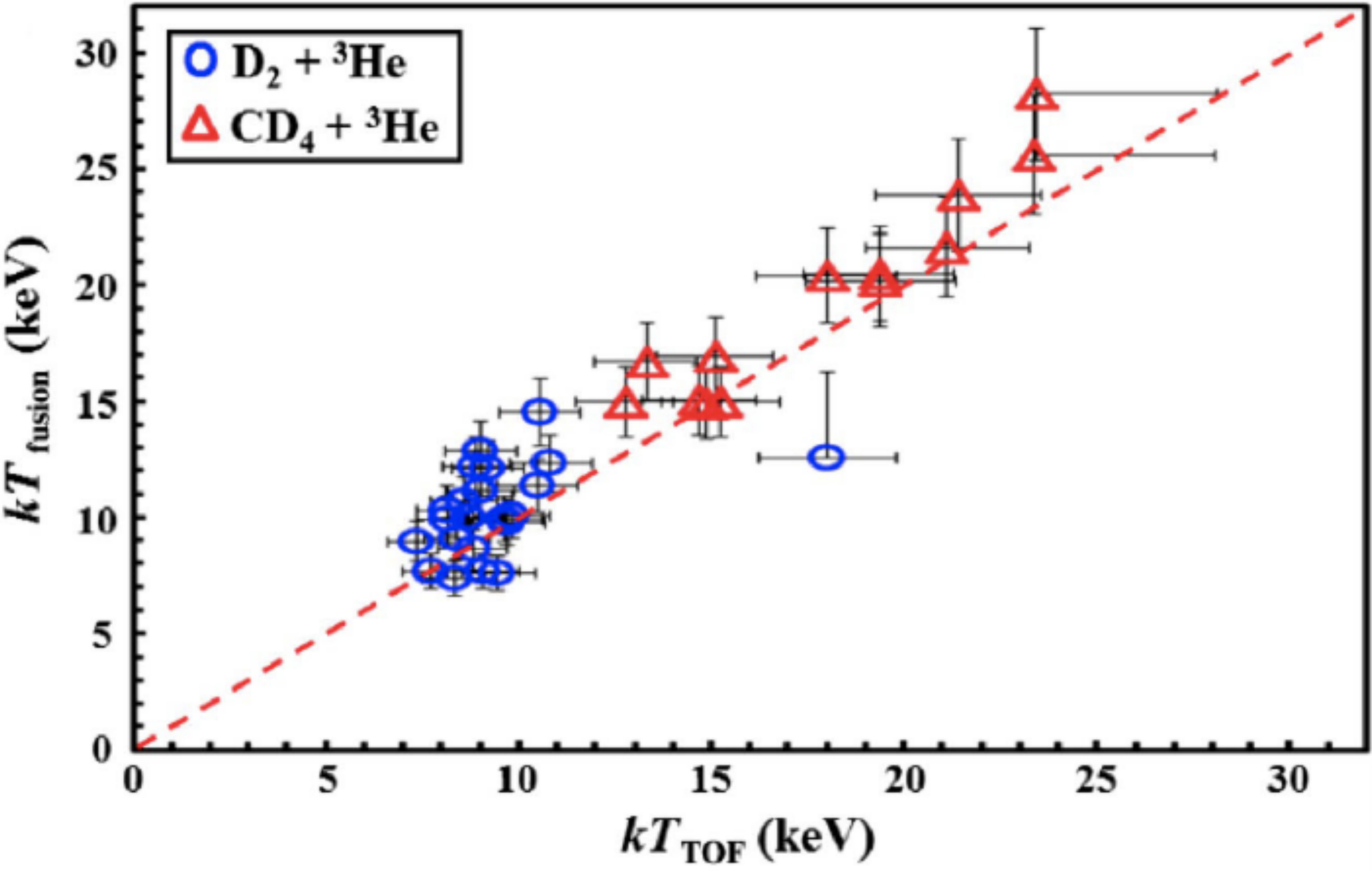
[1]*Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, Texas 78712, USA*
[2]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[3]*LNS-INFN, Via S. Sofia 64, 95123 Catania, Italy*
[4]*Associazione Euratom-ENEA sulla Fusione, via E. Fermi 45, CP 65-00044 Frascati (Rome), Italy*
[5]*Physics Department, University of Padova and INFN, I-35131 Padova, Italy*
[6]*Heavy Ions Laboratory, University of Warsaw, ul. Pasteura 5a, 02-093 Warszawa, Poland*

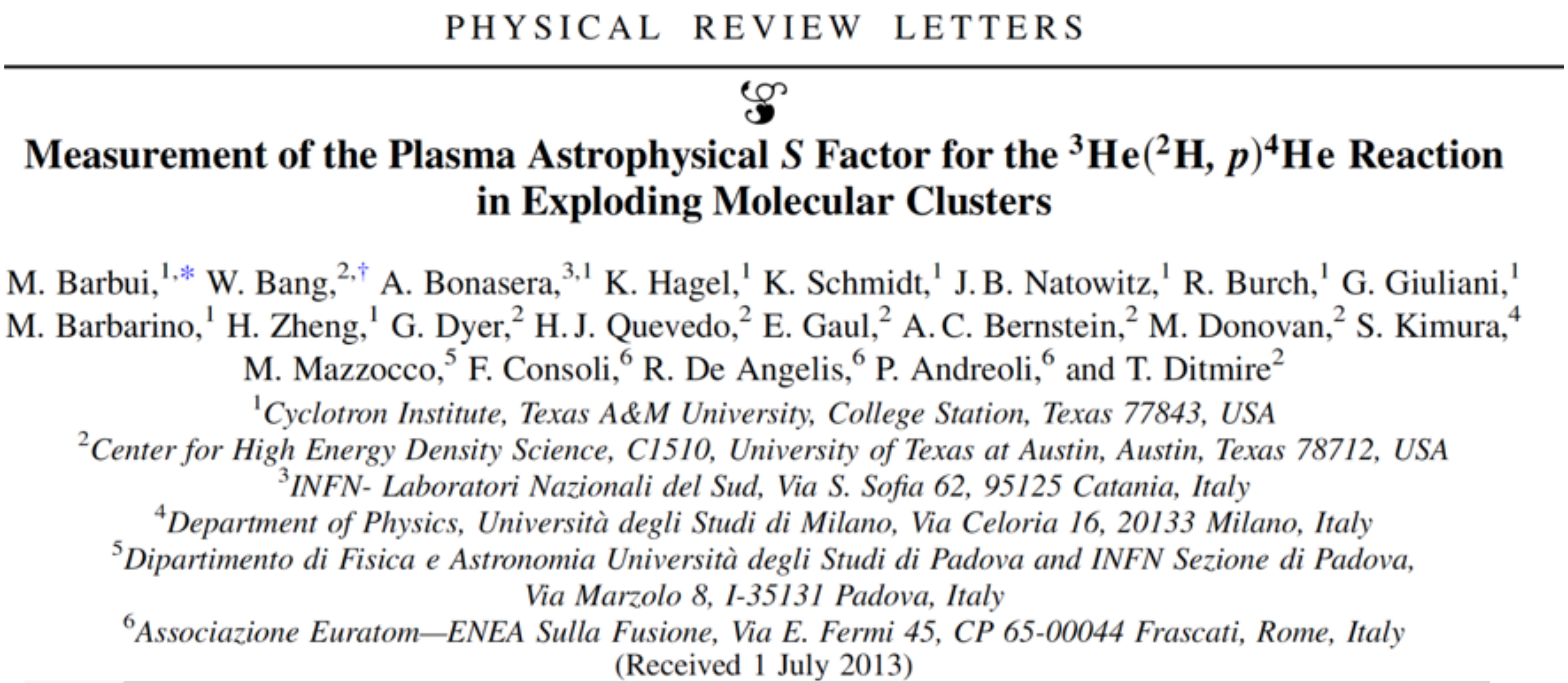
(Received 25 February 2013; published 30 July 2013)

Two different methods have been employed to determine the plasma temperature in a laser-cluster fusion experiment on the Texas Petawatt laser. In the first, the temperature was derived from time-of-flight data of deuterium ions ejected from exploding D_2 or CD_4 clusters. In the second, the temperature was measured from the ratio of the rates of two different nuclear fusion reactions occurring in the plasma at the same time: $D(d, {}^3He)n$ and ${}^3He(d, p){}^4He$. The temperatures determined by these two methods agree well, which indicates that (i) the ion energy distribution is not significantly distorted when ions travel in the disassembling plasma; (ii) the kinetic energy of deuterium ions, especially the "hottest part" responsible for nuclear fusion, is well described by a near-Maxwellian distribution.

DOI: 10.1103/PhysRevLett.111.055002 PACS numbers: 52.50.Jm, 25.45.−z, 36.40.Wa

Nuclear fusion from explosions of laser-heated clusters has been an active research topic for over a decade [1–11]. Researchers have used explosions of cryogenically cooled deuterium (D_2) cluster targets or near-room-temperature deuterated methane cluster plasmas produced by the irradiation of a clustering gas jet by 150 fs petawatt peak power laser pulses. We find that the effective ion temperature produced can be in excess of 25 keV.


○ $D_2 + {}^3He$
△ $CD_4 + {}^3He$
kT_{fusion} (keV)
kT_{TOF} (keV)
0
5
10
15
20
25
30
0
5
10
15
20
25
30



PHYSICAL REVIEW LETTERS

Measurement of the Plasma Astrophysical S Factor for the $^3He(^2H, p)^4He$ Reaction in Exploding Molecular Clusters

M. Barbui,[1,*] W. Bang,[2,†] A. Bonasera,[3,1] K. Hagel,[1] K. Schmidt,[1] J. B. Natowitz,[1] R. Burch,[1] G. Giuliani,[1]
M. Barbarino,[1] H. Zheng,[1] G. Dyer,[2] H. J. Quevedo,[2] E. Gaul,[2] A. C. Bernstein,[2] M. Donovan,[2] S. Kimura,[4]
M. Mazzocco,[5] F. Consoli,[6] R. De Angelis,[6] P. Andreoli,[6] and T. Ditmire[2]

[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[2]*Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, Texas 78712, USA*
[3]*INFN- Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy*
[4]*Department of Physics, Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy*
[5]*Dipartimento di Fisica e Astronomia Università degli Studi di Padova and INFN Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy*
[6]*Associazione Euratom—ENEA Sulla Fusione, Via E. Fermi 45, CP 65-00044 Frascati, Rome, Italy*

(Received 1 July 2013)

Synopsis: Nuclear Reactions in Lab Plasma

Courtesy M. Barbui/Texas A&M University

Measurement of the Plasma Astrophysical *S* Factor for the $^3He(d,p)^4He$ Reaction in Exploding Molecular Clusters
M. Barbui, W. Bang, A. Bonasera, K. Hagel, K. Schmidt, J. B. Natowitz, R. Burch, G. Giuliani, M. Barbarino, H. Zheng, G. Dyer, H. J. Quevedo, E. Gaul, A. C. Bernstein, M. Donovan, S. Kimura, M. Mazzocco, F. Consoli, R. De Angelis, P. Andreoli, and T. Ditmire
Phys. Rev. Lett. **111**, 082502 (2013)
Published August 22, 2013

Many low-energy nuclear reactions in astrophysics occur in plasmas, in which the nuclei are free of electrons. By contrast, most nuclear experiments involve neutral targets, whose bound electrons produce a "screening effect." A new technique uses lasers to remove these unwanted electrons so that low-energy nuclear reactions can be studied directly in laboratory plasma. The authors demonstrate their approach in *Physical Review Letters* on the deuterium/helium-3 interaction that helped synthesize elements in the early Universe and could potentially be used to power a future nuclear fusion reactor.

In a typical nuclear reaction experiment, an ion beam is directed at a target containing neutral atoms. The bound electrons provide a screen that reduces the Coulomb repulsion between the positive nuclei. Therefore, laboratory measurements tend to predict higher reaction rates than would be expected between ionized nuclei. To obtain astrophysically relevant parameters, researchers try to correct their data by estimating the screening effect of the bound electrons.

PHYSICAL REVIEW C **93**, 045808 (2016)

Model-independent determination of the astrophysical S factor in laser-induced fusion plasmas

D. Lattuada,[1,2,3,*] M. Barbarino,[1] A. Bonasera,[1,3] W. Bang,[4] H. J. Quevedo,[5] M. Warren,[1,6] F. Consoli,[7] R. De Angelis,[7]
P. Andreoli,[7] S. Kimura,[8] G. Dyer,[5] A. C. Bernstein,[5] K. Hagel,[1] M. Barbui,[1] K. Schmidt,[1,9] E. Gaul,[5] M. E. Donovan,[5]
J. B. Natowitz,[1] and T. Ditmire[5]
[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[2]*Università degli studi di Enna "Kore", 94100 Enna, Italy*
[3]*LNS-INFN, via S. Sofia, 62, 95123 Catania, Italy*
[4]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[5]*Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, Texas 78712, USA*
[6]*University of Dallas, Irving, Texas 75062, USA*
[7]*Associazione Euratom-ENEA sulla Fusione, via Enrico Fermi 45, CP 65-00044 Frascati, Rome, Italy*
[8]*Department of Physics, University of Milano, via Celoria 16, 20133 Milano, Italy*
[9]*Institute of Physics, University of Silesia, Katowice, Poland*

(Received 18 January 2016; published 19 April 2016)

In this work, we present a new and general method for measuring the astrophysical S factor of nuclear reactions in laser-induced plasmas and we apply it to $^{2}\mathrm{H}(d,n)^{3}\mathrm{He}$. The experiment was performed with the Texas Petawatt Laser, which delivered 150–270 fs pulses of energy ranging from 90 to 180 J to D_2 or CD_4 molecular clusters (where D denotes ^{2}H). After removing the background noise, we used the measured time-of-flight data of energetic deuterium ions to obtain their energy distribution. We derive the S factor using the measured energy distribution of the ions, the measured volume of the fusion plasma, and the measured fusion yields. This method is model independent in the sense that no assumption on the state of the system is required, but it requires an accurate measurement of the ion energy distribution, especially at high energies, and of the relevant fusion yields. In the $^{2}\mathrm{H}(d,n)^{3}\mathrm{He}$ and $^{3}\mathrm{He}(d,p)^{4}\mathrm{He}$ cases discussed here, it is very important to apply the background subtraction for the energetic ions and to measure the fusion yields with high precision. While the available data on both ion distribution and fusion yields allow us to determine with good precision the S factor in the $d+d$ case (lower Gamow energies), for the $d+{}^{3}\mathrm{He}$ case the data are not precise enough to obtain the S factor using this method. Our results agree with other experiments within the experimental error, even though smaller values of the S factor were obtained. This might be due to the plasma environment differing from the beam target conditions in a conventional accelerator experiment.

DOI: 10.1103/PhysRevC.93.045808

I. INTRODUCTION

The nuclear reactions between light nuclei in the low energy region (∼ keV),

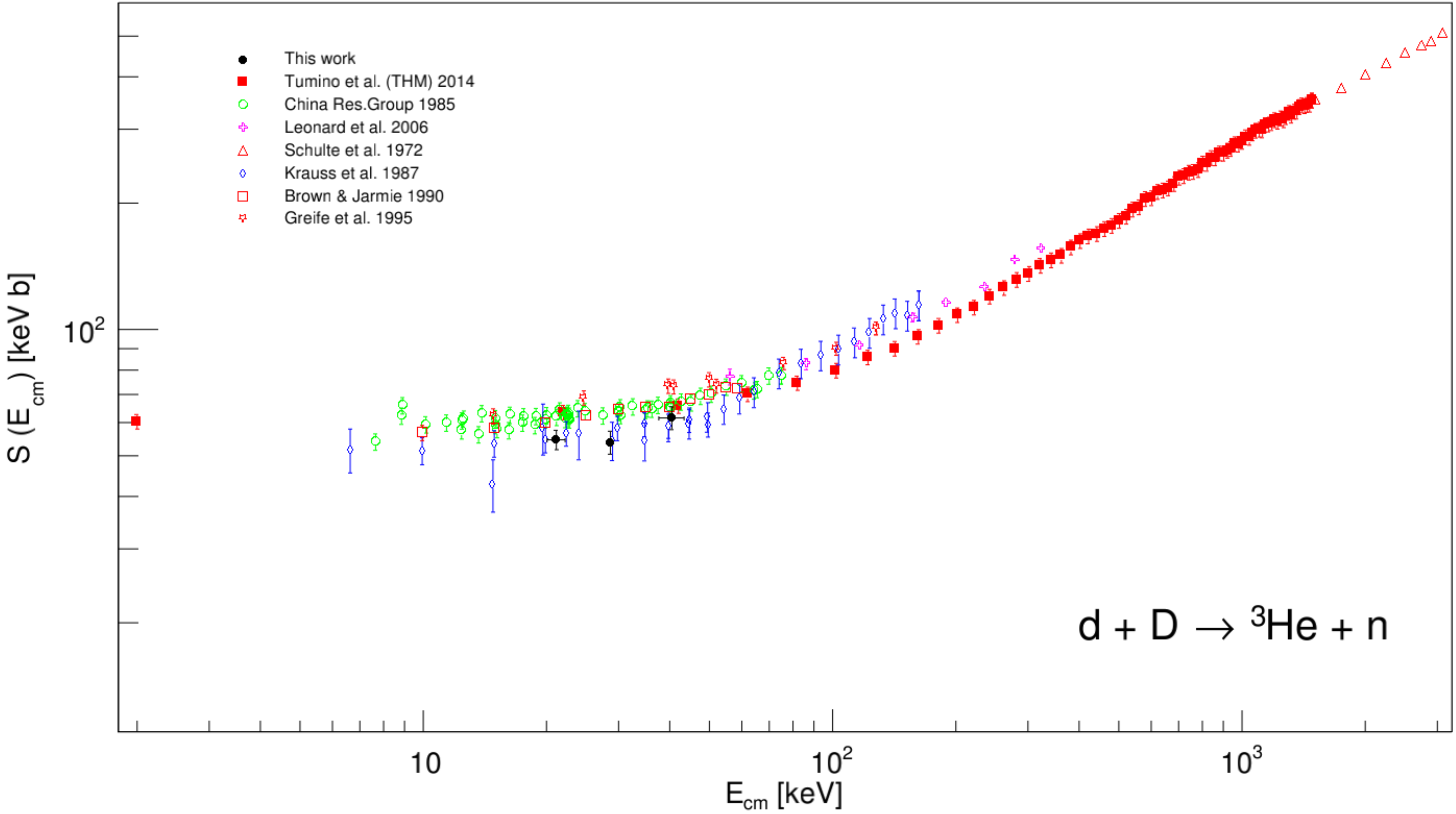
$$d+d \to {}^{3}\mathrm{He}(0.82\ \mathrm{MeV})+n(2.45\ \mathrm{MeV}), \qquad (1)$$

$$d+d \to p(3.02\ \mathrm{MeV})+t(1.01\ \mathrm{MeV}), \qquad (2)$$

$$d+{}^{3}\mathrm{He} \to p(14.7\ \mathrm{MeV})+{}^{4}\mathrm{He}(3.6\ \mathrm{MeV}). \qquad (3)$$

have been studied for many decades [1–10]. The role of low-energy nuclear physics is crucial in both astrophysics, playing a key role in the determination of primordial abundances in Big Bang nucleosynthesis (BBN) models, and applied (plasma) physics, as it lies in the energy region of interest for the operation and design of future fusion power plants. Direct and with bare nuclei and with the ones occurring in astrophysical plasmas [1,6,13,14].

Other physical conditions are possible which might decrease the astrophysical factor, dubbed the dissipative limit (DL) in [11,12]. In a hot plasma, due to the large number of positive and negative charges, fusions occurring in an "electron" cloud might be enhanced. If, however, a large number of positive charges is present in the region where fusion occurs, then the cross section might decrease. In laser-cluster interactions we might be able to create such conditions, thus it would represent a good chance to study the fusion cross sections within stellar plasmas in a laboratory. In particular, we can explore temperatures ranging from few keV up to few tens of keV and a density just above 10^{18} atoms/cm^3. These


This work
Tumino et al. (THM) 2014
China Res.Group 1985
Leonard et al. 2006
Schulte et al. 1972
Krauss et al. 1987
Brown & Jarmie 1990
Greife et al. 1995
S (E_cm) [keV b]
10^2
10
10^2
10^3
E_cm [keV]
d + D → ^3He + n

Physics Letters A 381 (2017) 1682–1686

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Range of plasma ions in cold cluster gases near the critical point

G. Zhang [a,1], H.J. Quevedo [b], A. Bonasera [a,c,*], M. Donovan [b], G. Dyer [b], E. Gaul [b], G.L. Guardo [c], M. Gulino [c,d], M. La Cognata [c], D. Lattuada [c], S. Palmerini [e,f], R.G. Pizzone [c], S. Romano [c], H. Smith [b], O. Trippella [e,f], A. Anzalone [c], C. Spitaleri [c], T. Ditmire [b]

[a] *Cyclotron Institute, Texas A&M University, 77843 College Station, TX, USA*
[b] *Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, TX 78712, USA*
[c] *Laboratori Nazionali del Sud-INFN, via S. Sofia 64, 95123 Catania, Italy*
[d] *Libera Universita' Kore, 94100 Enna, Italy*
[e] *Department of Physics and Geology, University of Perugia, Via A. Pascoli, 06123 Perugia, Italy*
[f] *Istituto Nazionale di Fisica Nucleare, Section of Perugia, Via A. Pascoli, 06123 Perugia, Italy*

ARTICLE INFO

Article history:
Received 27 February 2017
Accepted 12 March 2017
Available online 18 March 2017
Communicated by F. Porcelli

Keywords:
Range of plasma ions in cold cluster gases
Petawatt laser interaction with cluster gases
Ion range in systems prepared near a liquid–gas phase transition

ABSTRACT

We measure the range of plasma ions in cold cluster gases by using the Petawatt laser at the University of Texas-Austin. The produced plasma propagated in all directions some hitting the cold cluster gas not illuminated by the laser. From the ratio of the measured ion distributions at different angles we can estimate the range of the ions in the cold cluster gas. It is much smaller than estimated using popular models, which take only into account the slowing down of charged particles in uniform matter. We discuss the ion range in systems prepared near a liquid–gas phase transition.

Nuclear fusion from explosions of laser-heated clusters has been an active research topic for over a decade [1–14]. The explosions of cryogenically cooled deuterium (D_2) cluster targets or near-room-temperature deuterium-methane (CD_4) cluster targets drive fusion reactions. A high intensity femtosecond laser pulse irradiated the cluster gas. This produces energetic explosions of the clusters and tens of keV ion plasma temperature results. DD fusion occurring within this high temperature plasma combined with beam-target fusion, between the ejected ions of the cluster and surrounding cold cluster gas, leads to a burst of fusion neutrons and protons. Following these experiments, we have modified some aspects in order to be able to measure the range of energetic ions in the cold cluster gases. Recall that the range of ions is crucial to estimate the fusion rates in the plasma. We have opportunely focused the laser in such a way that the high-energy pulse drills a "hole" in the target. We found that less than 10% of the laser energy went through the cluster gas for each shot.

A schematic view of this scenario is plotted in Fig. 1a, while an actual experimental result is given in Fig. 1b. Two Faraday cups (FC) were opportunely located: the first one (UTFC) as close as possible to the incoming laser direction (−67.5° minimum) thus measuring essentially the hot plasma only; the second one (CTFC) was located at an angle around 45°, see Fig. 1, and compatible to the physical constraints of the laboratory (walls). The ratio of the FC signals gives an indication of the range of the ions in the surrounding cold cluster gas. Our experimental results show that *the range of the ions in the cluster gas is almost independent of their energies and it is much shorter than the range calculated using the popular SRIM code for instance* [15]. The physics included in SRIM or similar models, is the slowing down of keV ions due to the interaction with electrons in the uniform gas. In our case, the gas has not an uniform density distribution but it is made of drops of different sizes, well explained by a log-normal distribution [16,17], formed during the free expansion into vacuum after the opening of the pulsed valve. Drops can present already inside the valve before the expansion, if the gas is prepared for instance near the critical point of the liquid–gas (LG) phase transition. It is of great interest to study what happens in those cases after the gas expands. Near the second order LG phase transition, the mass distribution of the clusters follows the Fisher's law and in particular it is a power law at the critical point [18]. The free expansion might change such distribution. Theoretical calculations of a classical interacting gas, which freely expands after has been prepared near the critical point [19], do not display much variation from the predicted Fisher's cluster distribution. Thus, the cluster size distribution obtained from the

---

* Corresponding author.
E-mail address: abonasera@comp.tamu.edu (A. Bonasera).

[1] On leave from SINAP, Shanghai, China.

http://dx.doi.org/10.1016/j.physleta.2017.03.016
0375-9601/© 2017 Elsevier B.V. All rights reserved.

Physics Letters A 382 (2018) 94–98

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Neutron enhancement from laser interaction with a critical fluid

H.J. Quevedo[a], G. Zhang[b,1], A. Bonasera[b,c,*], M. Donovan[a], G. Dyer[a], E. Gaul[a], G.L. Guardo[c], M. Gulino[c,d], M. La Cognata[c], D. Lattuada[c], S. Palmerini[e,f], R.G. Pizzone[c], S. Romano[c], H. Smith[a], O. Trippella[e,f], A. Anzalone[c], C. Spitaleri[c], T. Ditmire[a]

[a] *Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, TX 78712, USA*
[b] *Cyclotron Institute, Texas A&M University, 77843 College Station, TX, USA*
[c] *Laboratori Nazionali del Sud-INFN, via S. Sofia 64, 95123 Catania, Italy*
[d] *Libera Universita' Kore, 94100 Enna, Italy*
[e] *Department of Physics and Geology, University of Perugia, Via A. Pascoli, 06123 Perugia, Italy*
[f] *Istituto Nazionale di Fisica Nucleare, Section of Perugia, Via A. Pascoli, 06123 Perugia, Italy*

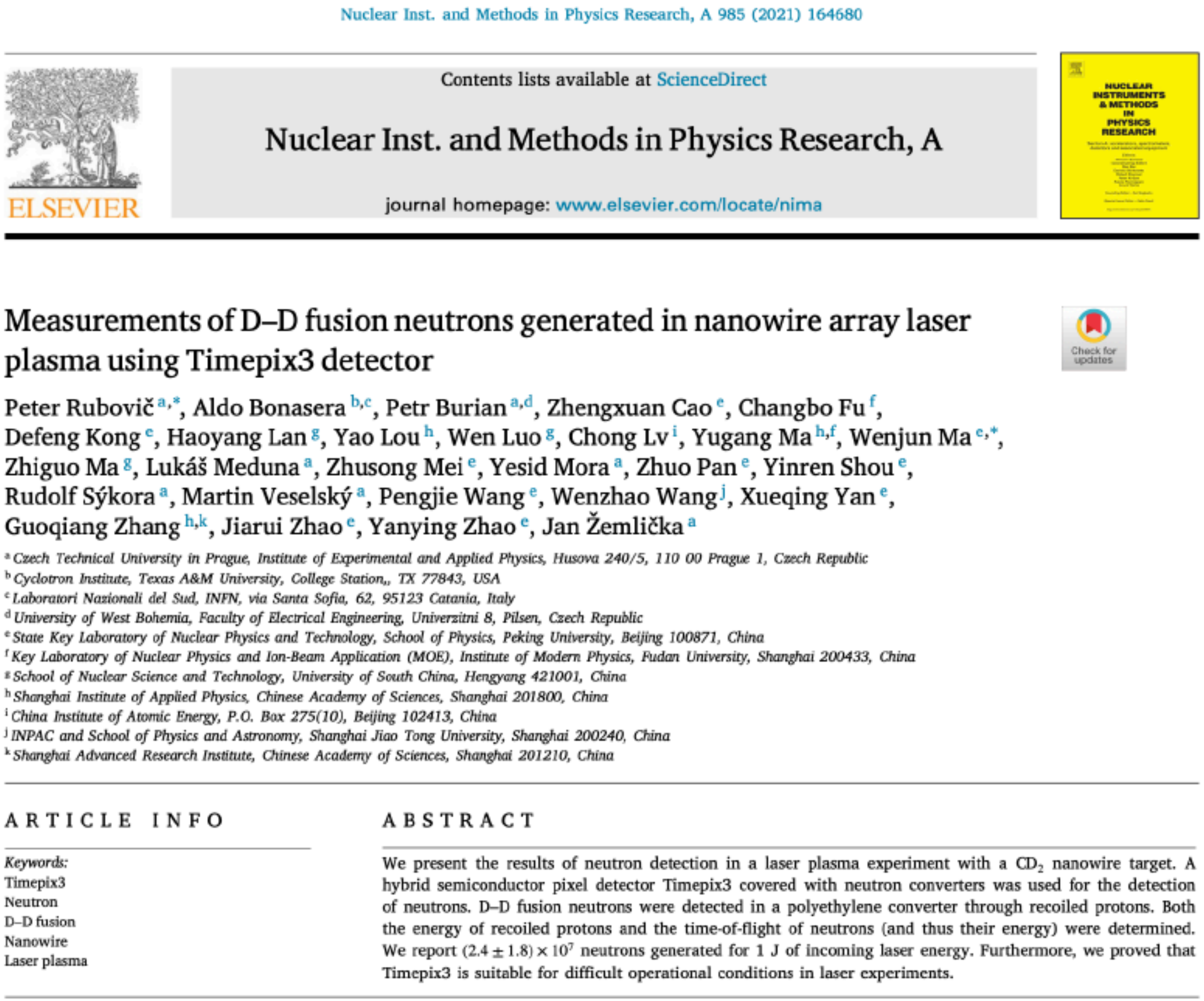
ARTICLE INFO

Article history:
Received 10 April 2017
Received in revised form 5 September 2017
Accepted 3 November 2017
Available online 7 November 2017
Communicated by F. Porcelli

Keywords:
Laser induced plasma
Critical phenomena
Fusion reactions

ABSTRACT

We discuss experimentally and theoretically neutron production from the laser driven explosion of gas clusters prepared near the liquid-gas critical point. We let deuterated methane that was prepared very close to its critical temperature and pressure expand through a conical nozzle to create clusters, and then irradiated those clusters with a high intensity pulse from the Texas Petawatt Laser. After ionization, the clusters explode producing energetic ions, some of which fuse with resultant neutron emission. We show that the critical fluctuations present in the nozzle before the expansion influence the dynamics of neutron production. Neutron production near the critical point follows a power law, which is a signature of a second order phase transition and it is consistent with the Fisher model. This result might be relevant for energy production from fusion reactions.



Nuclear Inst. and Methods in Physics Research, A 985 (2021) 164680

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Measurements of D–D fusion neutrons generated in nanowire array laser plasma using Timepix3 detector

Peter Rubovič [a,*], Aldo Bonasera [b,c], Petr Burian [a,d], Zhengxuan Cao [e], Changbo Fu [f], Defeng Kong [e], Haoyang Lan [g], Yao Lou [h], Wen Luo [g], Chong Lv [i], Yugang Ma [h,f], Wenjun Ma [e,*], Zhiguo Ma [g], Lukáš Meduna [a], Zhusong Mei [e], Yesid Mora [a], Zhuo Pan [e], Yinren Shou [e], Rudolf Sýkora [a], Martin Veselský [a], Pengjie Wang [e], Wenzhao Wang [j], Xueqing Yan [e], Guoqiang Zhang [h,k], Jiarui Zhao [e], Yanying Zhao [e], Jan Žemlička [a]

[a] Czech Technical University in Prague, Institute of Experimental and Applied Physics, Husova 240/5, 110 00 Prague 1, Czech Republic
[b] Cyclotron Institute, Texas A&M University, College Station,, TX 77843, USA
[c] Laboratori Nazionali del Sud, INFN, via Santa Sofia, 62, 95123 Catania, Italy
[d] University of West Bohemia, Faculty of Electrical Engineering, Univerzitni 8, Pilsen, Czech Republic
[e] State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China
[f] Key Laboratory of Nuclear Physics and Ion-Beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[g] School of Nuclear Science and Technology, University of South China, Hengyang 421001, China
[h] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[i] China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413, China
[j] INPAC and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
[k] Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China

ARTICLE INFO

Keywords:
Timepix3
Neutron
D–D fusion
Nanowire
Laser plasma

ABSTRACT

We present the results of neutron detection in a laser plasma experiment with a CD_2 nanowire target. A hybrid semiconductor pixel detector Timepix3 covered with neutron converters was used for the detection of neutrons. D–D fusion neutrons were detected in a polyethylene converter through recoiled protons. Both the energy of recoiled protons and the time-of-flight of neutrons (and thus their energy) were determined. We report $(2.4 \pm 1.8) \times 10^7$ neutrons generated for 1 J of incoming laser energy. Furthermore, we proved that Timepix3 is suitable for difficult operational conditions in laser experiments.

NEXT

Nuclear Inst. and Methods in Physics Research, A 985 (2021) 164680

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

NEXT

Measurements of D–D fusion neutrons generated in nanowire arra plasma using Timepix3 detector

Peter Rubovič [a,*], Aldo Bonasera [b,c], Petr Burian [a,d], Zhengxuan Cao [e], Changbo Fu [f], Defeng Kong [e], Haoyang Lan [g], Yao Lou [h], Wen Luo [g], Chong Lv [i], Yugang Ma [h,f], We Zhiguo Ma [g], Lukáš Meduna [a], Zhusong Mei [e], Yesid Mora [a], Zhuo Pan [e], Yinren Sho Rudolf Sýkora [a], Martin Veselský [a], Pengjie Wang [e], Wenzhao Wang [j], Xueqing Yan Guoqiang Zhang [h,k], Jiarui Zhao [e], Yanying Zhao [e], Jan Žemlička [a]

[a] *Czech Technical University in Prague, Institute of Experimental and Applied Physics, Husova 240/5, 110 00 Prague 1, Czech Republic*
[b] *Cyclotron Institute, Texas A&M University, College Station,, TX 77843, USA*
[c] *Laboratori Nazionali del Sud, INFN, via Santa Sofia, 62, 95123 Catania, Italy*
[d] *University of West Bohemia, Faculty of Electrical Engineering, Univerzitni 8, Pilsen, Czech Republic*
[e] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[f] *Key Laboratory of Nuclear Physics and Ion-Beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433,*
[g] *School of Nuclear Science and Technology, University of South China, Hengyang 421001, China*
[h] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*
[i] *China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413, China*
[j] *INPAC and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[k] *Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China*

ARTICLE INFO

Keywords:
Timepix3
Neutron
D–D fusion
Nanowire
Laser plasma

ABSTRACT

We present the results of neutron detection in a laser plasma ex hybrid semiconductor pixel detector Timepix3 covered with neutr of neutrons. D–D fusion neutrons were detected in a polyethylene the energy of recoiled protons and the time-of-flight of neutrons We report $(2.4 \pm 1.8) \times 10^7$ neutrons generated for 1 J of incoming Timepix3 is suitable for difficult operational conditions in laser ex

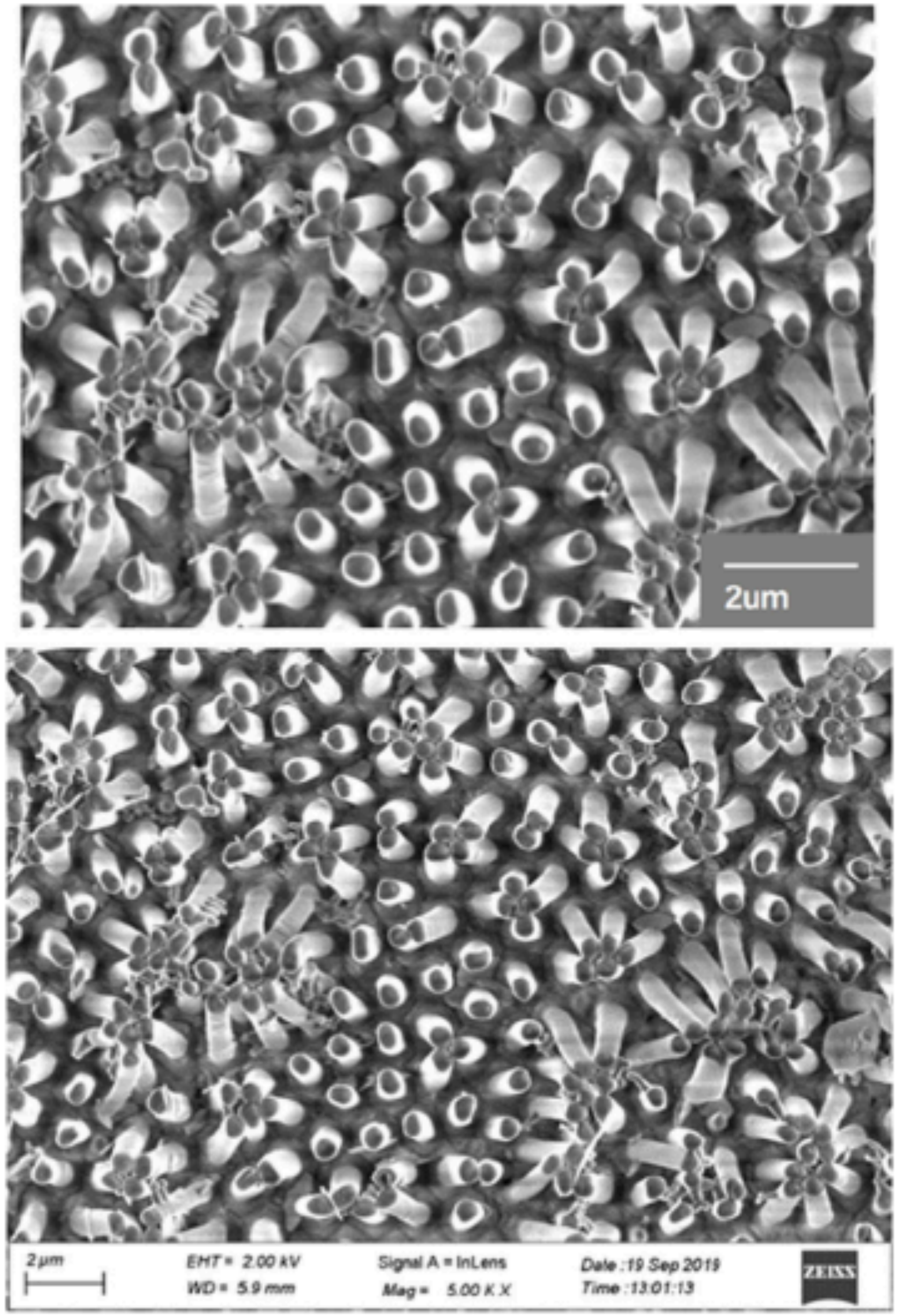


Fig. 2. The SEM image of the DPE nanowires array target with 500 nm diameter, 800 nm spacing and 5 µm length.

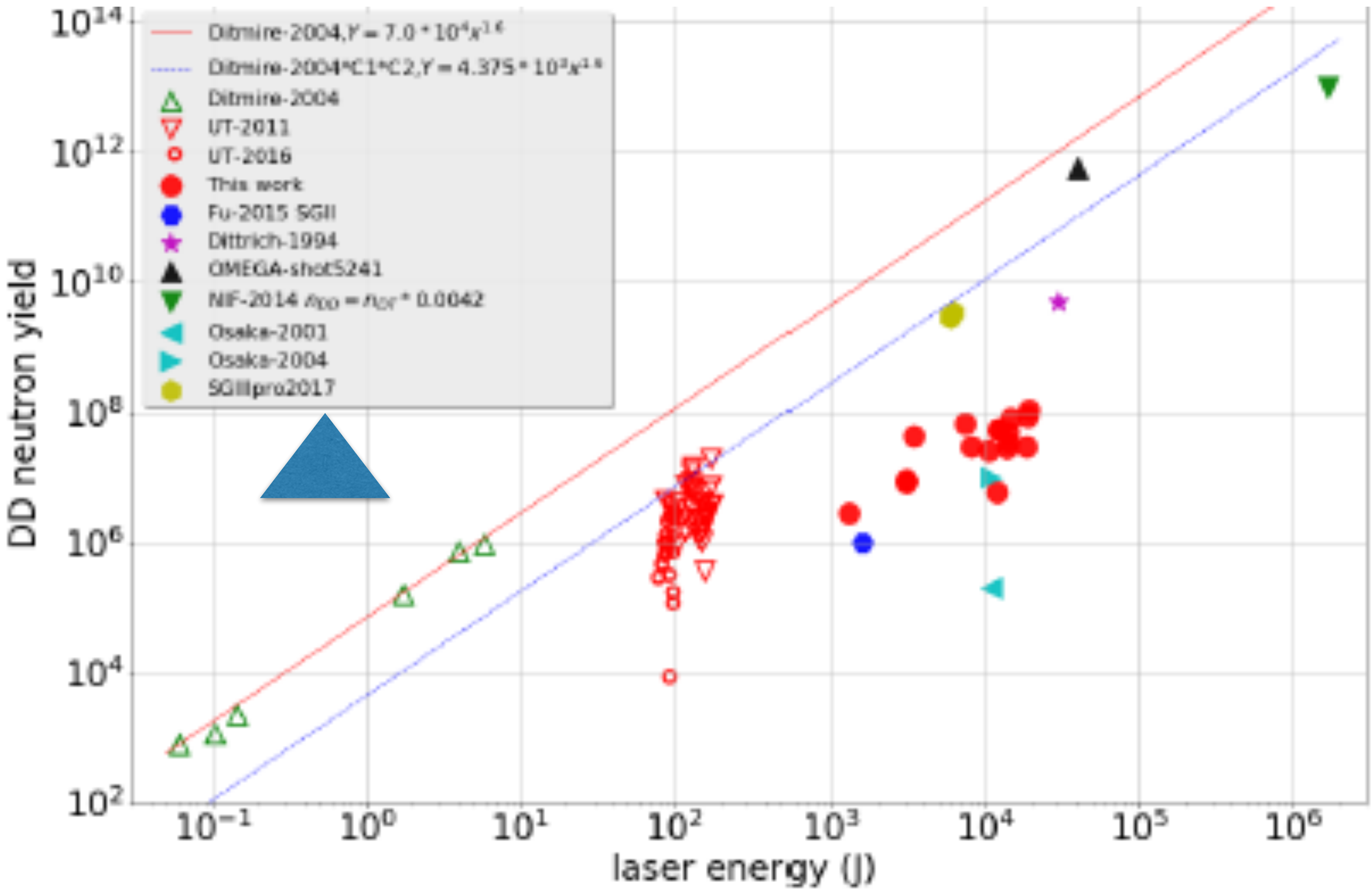
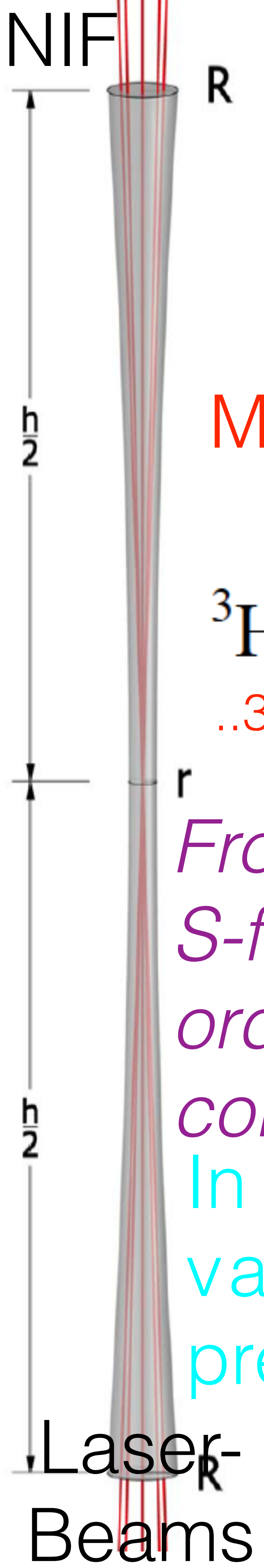


Figure 3: (color online) Fusion yield as function of laser energy. Different experimental results Ditmire-
UT-2011[20], UT-2016[19], Fu-2015 SGII[40], Dittrich-1994[44] , NIF-2014[43] , Osaka -2001[41], Osaka-2004[42], O
shot5241[36]and SGIIIpro2017[37] are indicated in the inset.



Cryogenic d+t Target or solid ^{6}Lid(t)

Measure plasma ions kinetic energy distribution: determine non-equilibrium and thermal components

Measure number of fusions in

$d+t \longrightarrow a+n$

$d+d \longrightarrow {}^{3}He+n(t+p)$

$t+t \longrightarrow a+2n$

$^{3}He+d \rightarrow \alpha+p.$

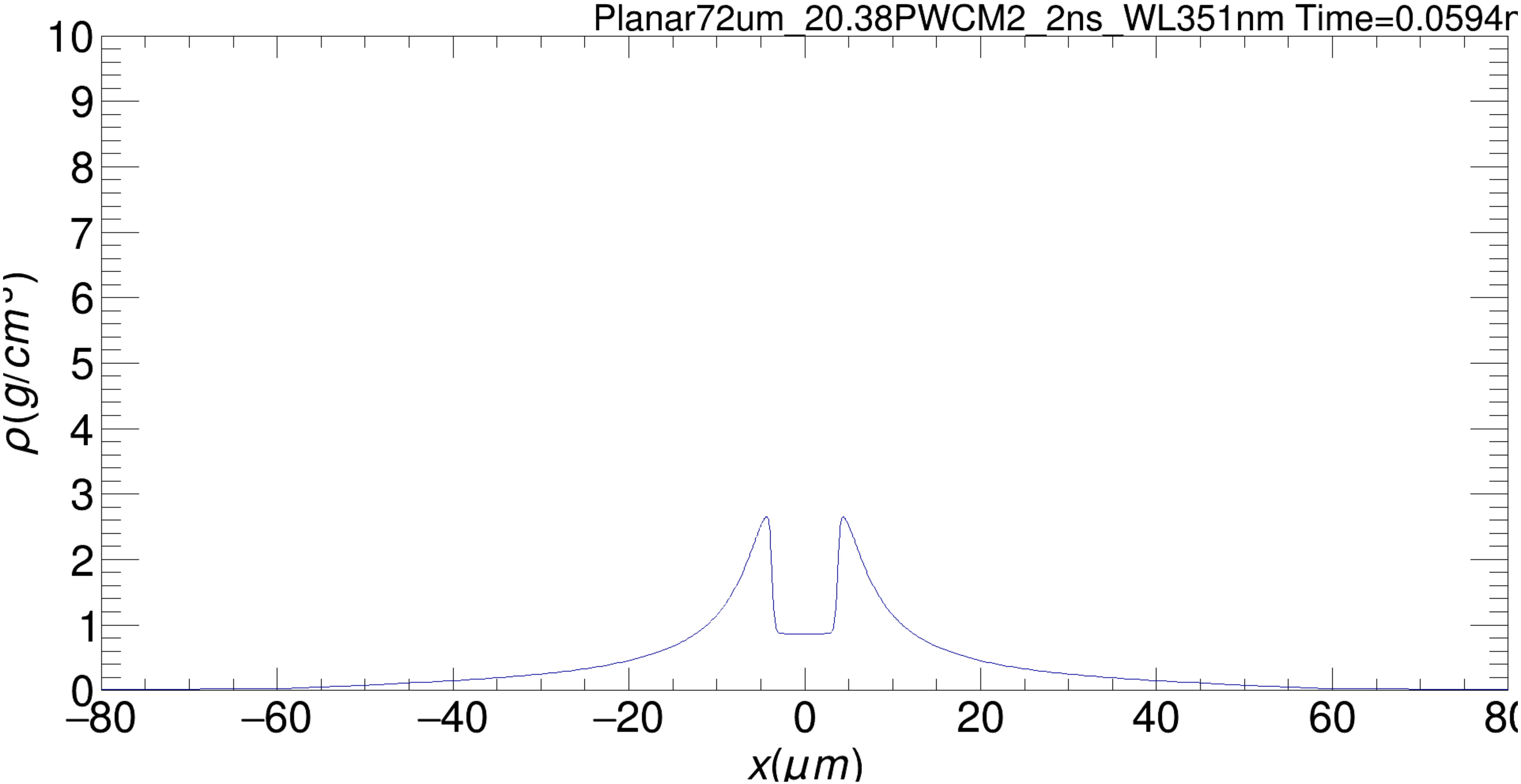
$t+\alpha \rightarrow {}^{7}Li+\gamma$

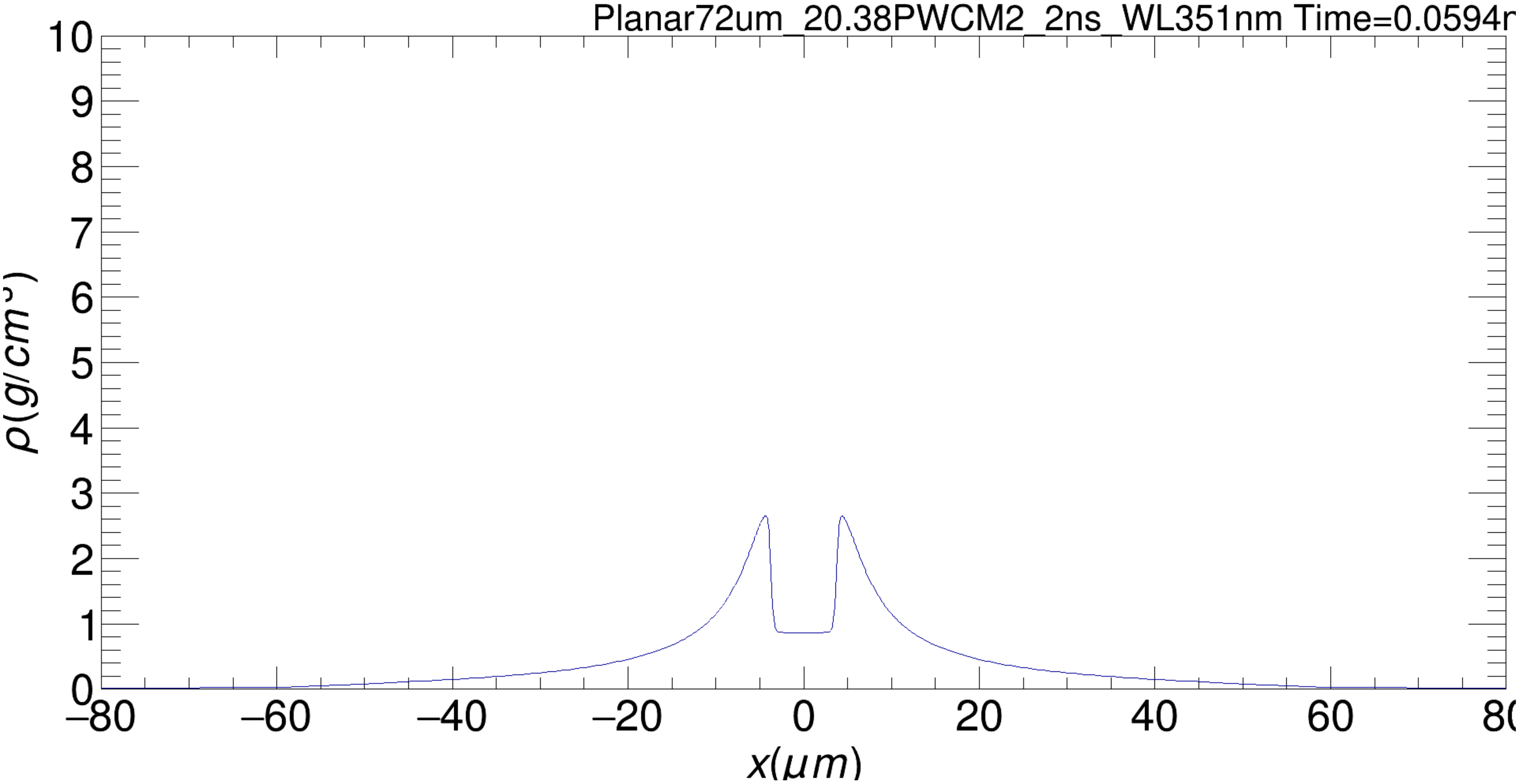
$^{3}He+\alpha \rightarrow {}^{7}Be+\gamma$ $^{7}Li+t \rightarrow {}^{9}Be+n$ $^{9}Be+\alpha \rightarrow {}^{12}C+n$ $n+{}^{7}Be \rightarrow 2\alpha$

..3rd,4th …order nuclear reactions.Some reaction can be measured, some NOT.

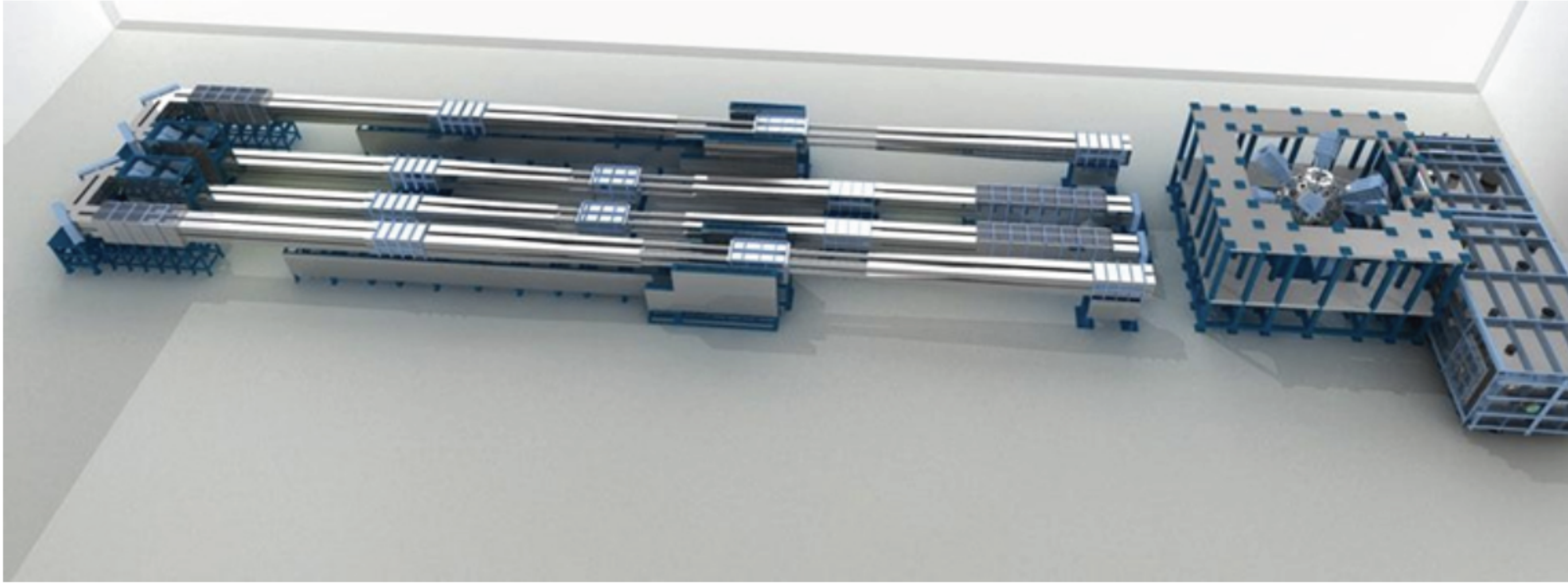
From these informations we can derive the astrophysical S-factor for the main channels and some of the higher order reactions as function of temperature, density and collective energy of the plasma.

In the 18 months we plan to perform 8 shots @ NIF with various targets-laser beams combinations and preliminary data analysis completed.


Planar72um_20.38PWCM2_2ns_WL351nm Time=0.0594r
$\rho(g/cm^3)$
0
1
2
3
4
5
6
7
8
9
10
−80
−60
−40
−20
0
20
40
60
80
$x(\mu m)$


Planar72um_20.38PWCM2_2ns_WL351nm Time=0.0594r
$\rho(g/cm^3)$
0
1
2
3
4
5
6
7
8
9
10
−80
−60
−40
−20
0
20
40
60
8
$x(\mu m)$

SGII-U



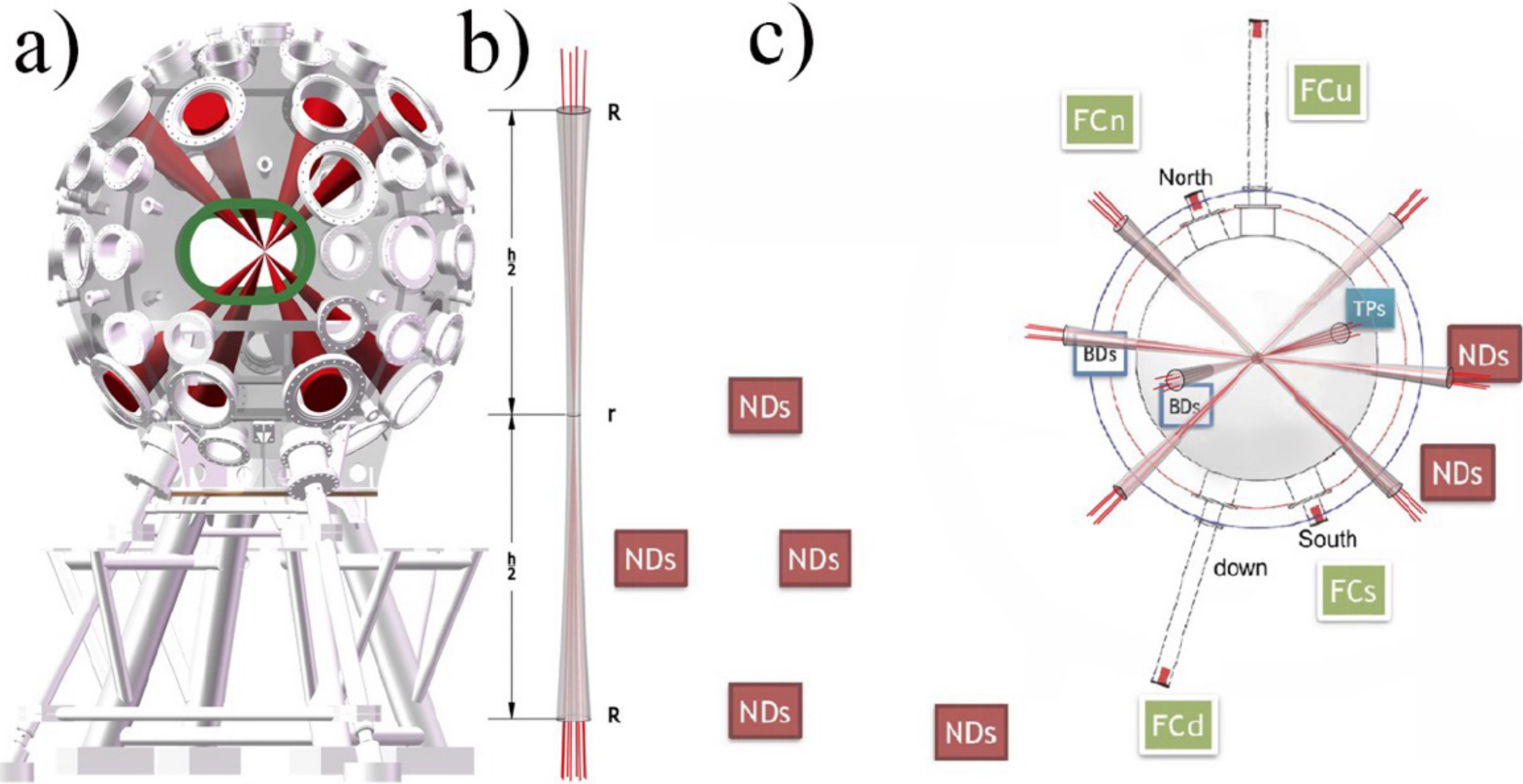
operating since 2011

8 beams output 40 kJ/3 ns/1 ω, 24 kJ/3 ns/3 ω

PW laser (1.5kJ, 2ps, 2011)

for SINAP\SIOM\TAMU\INFN\IMUN

Collaboration


a)
b)
R
h
2
r
h
2
R
c)
FCu
FCn
North
TPs
BDs
NDs
NDs
BDs
NDs
NDs
NDs
South
down
FCs
NDs
NDs
FCd

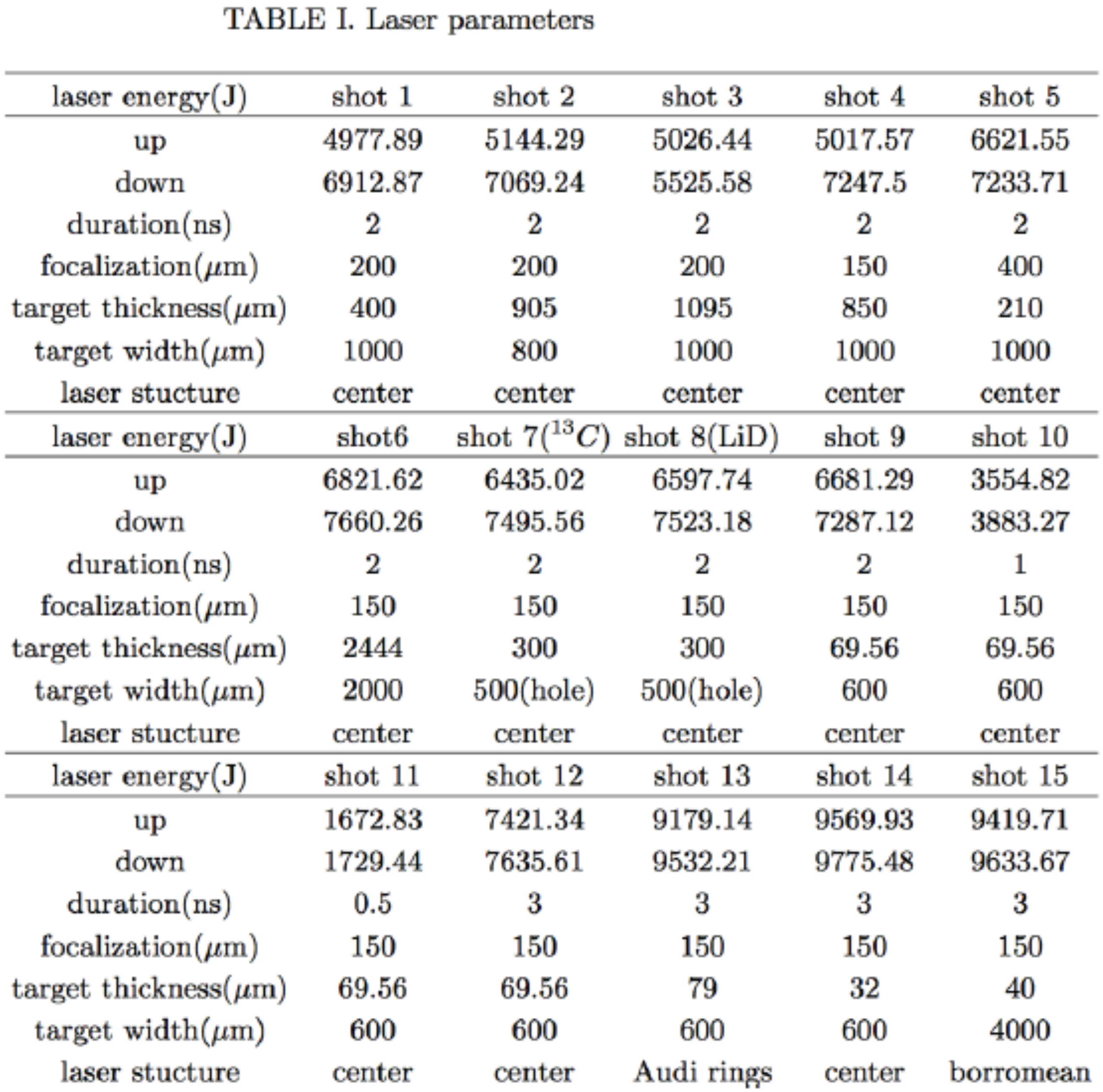
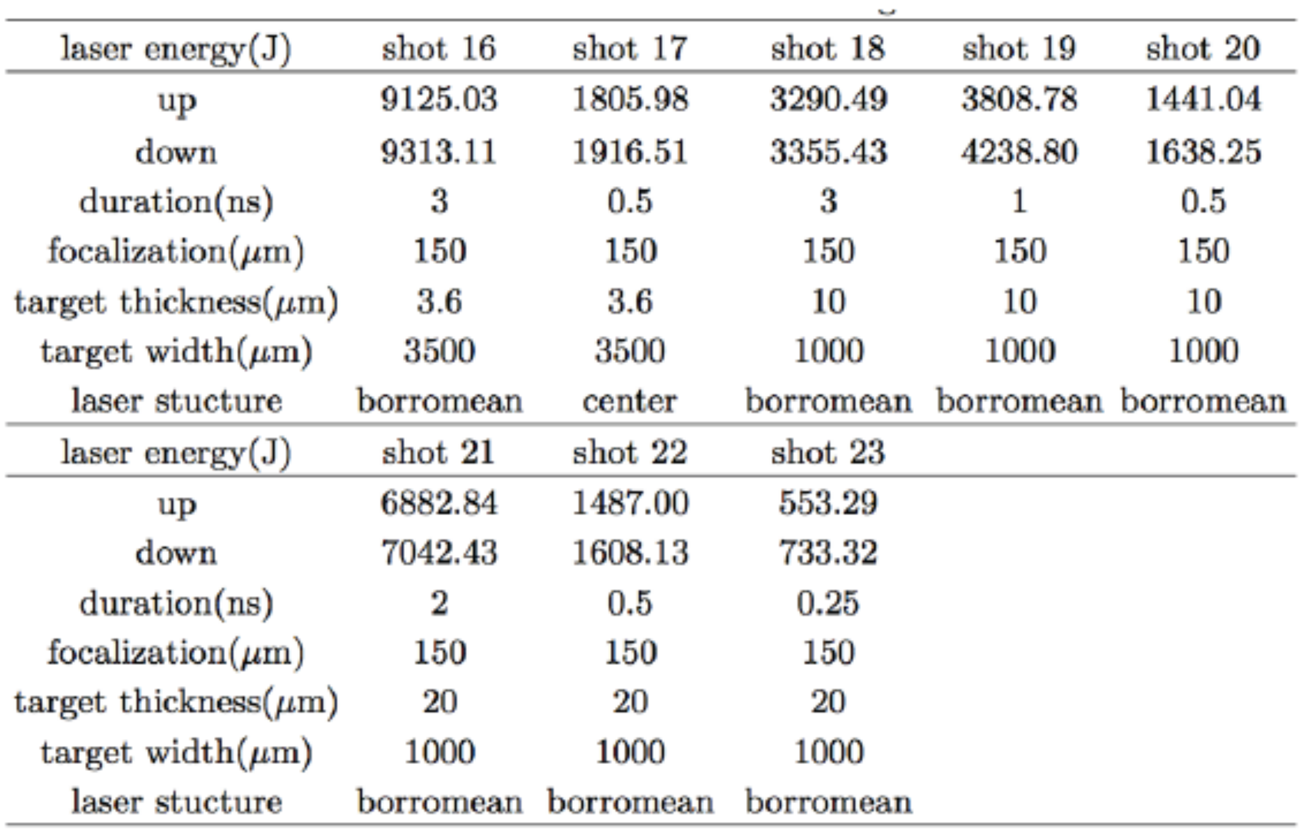
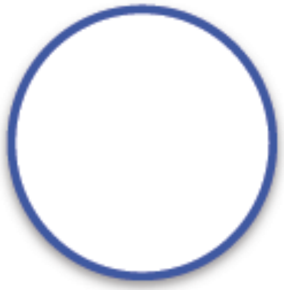


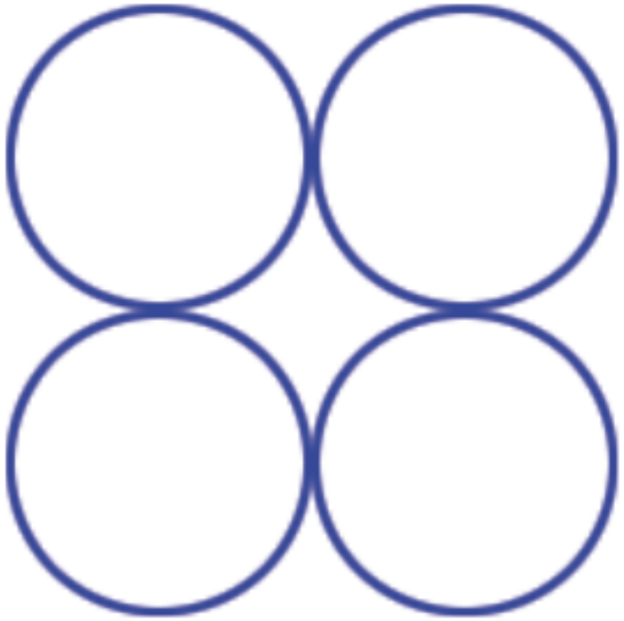
TABLE I. Laser parameters

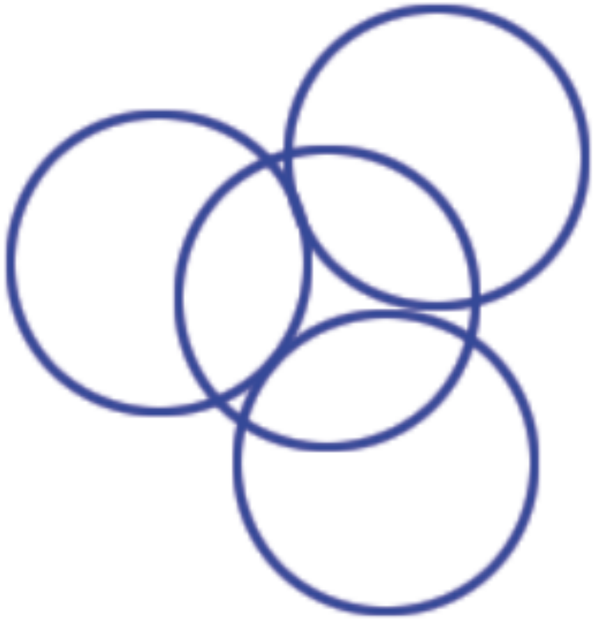
laser energy(J)	shot 1	shot 2	shot 3	shot 4	shot 5
up	4977.89	5144.29	5026.44	5017.57	6621.55
down	6912.87	7069.24	5525.58	7247.5	7233.71
duration(ns)	2	2	2	2	2
focalization(μm)	200	200	200	150	400
target thickness(μm)	400	905	1095	850	210
target width(μm)	1000	800	1000	1000	1000
laser stucture	center	center	center	center	center
laser energy(J)	**shot6**	**shot 7(^{13}C)**	**shot 8(LiD)**	**shot 9**	**shot 10**
up	6821.62	6435.02	6597.74	6681.29	3554.82
down	7660.26	7495.56	7523.18	7287.12	3883.27
duration(ns)	2	2	2	2	1
focalization(μm)	150	150	150	150	150
target thickness(μm)	2444	300	300	69.56	69.56
target width(μm)	2000	500(hole)	500(hole)	600	600
laser stucture	center	center	center	center	center
laser energy(J)	**shot 11**	**shot 12**	**shot 13**	**shot 14**	**shot 15**
up	1672.83	7421.34	9179.14	9569.93	9419.71
down	1729.44	7635.61	9532.21	9775.48	9633.67
duration(ns)	0.5	3	3	3	3
focalization(μm)	150	150	150	150	150
target thickness(μm)	69.56	69.56	79	32	40
target width(μm)	600	600	600	600	4000
laser stucture	center	center	Audi rings	center	borromean



laser energy(J)	shot 16	shot 17	shot 18	shot 19	shot 20
up	9125.03	1805.98	3290.49	3808.78	1441.04
down	9313.11	1916.51	3355.43	4238.80	1638.25
duration(ns)	3	0.5	3	1	0.5
focalization(μm)	150	150	150	150	150
target thickness(μm)	3.6	3.6	10	10	10
target width(μm)	3500	3500	1000	1000	1000
laser stucture	borromean	center	borromean	borromean	borromean
laser energy(J)	**shot 21**	**shot 22**	**shot 23**		
up	6882.84	1487.00	553.29		
down	7042.43	1608.13	733.32		
duration(ns)	2	0.5	0.25		
focalization(μm)	150	150	150		
target thickness(μm)	20	20	20		
target width(μm)	1000	1000	1000		
laser stucture	borromean	borromean	borromean		







zhangguoqiang2017-04-13 @SINAP

Cross sections\S-factor\reaction rate in plasmas

The effect of ternary fusion reactions

Highly compressed and not so hot plasma

$Nf1=Ni*\rho<\sigma v\tau>/2= Ni*\rho<\sigma 1>r1/2$ ———————————— (1)

$Nf2=Nf1*\rho<\sigma 2>r2$ ——————————————————— (2)

$d + d \rightarrow {}^{3}He$ (0.82 MeV) + n (2.45 MeV)

$d + d \rightarrow t$ (1.01MeV) + p (3.02 MeV)

$d + t \rightarrow {}^{4}He$ (3.5MeV) + n (14.1 MeV)

$d + {}^{3}He \rightarrow {}^{4}He$ (3.6MeV) + p (14.7 MeV)

0	Ni	d ρ <σ> r
1	Nf1	^{3}He (0.82 MeV) n (2.45 MeV) t (1.01MeV) p (3.02 MeV)
2	Nf2	^{4}He (3.5MeV) n (14.1 MeV) ^{4}He (3.6MeV) p (14.7 MeV)

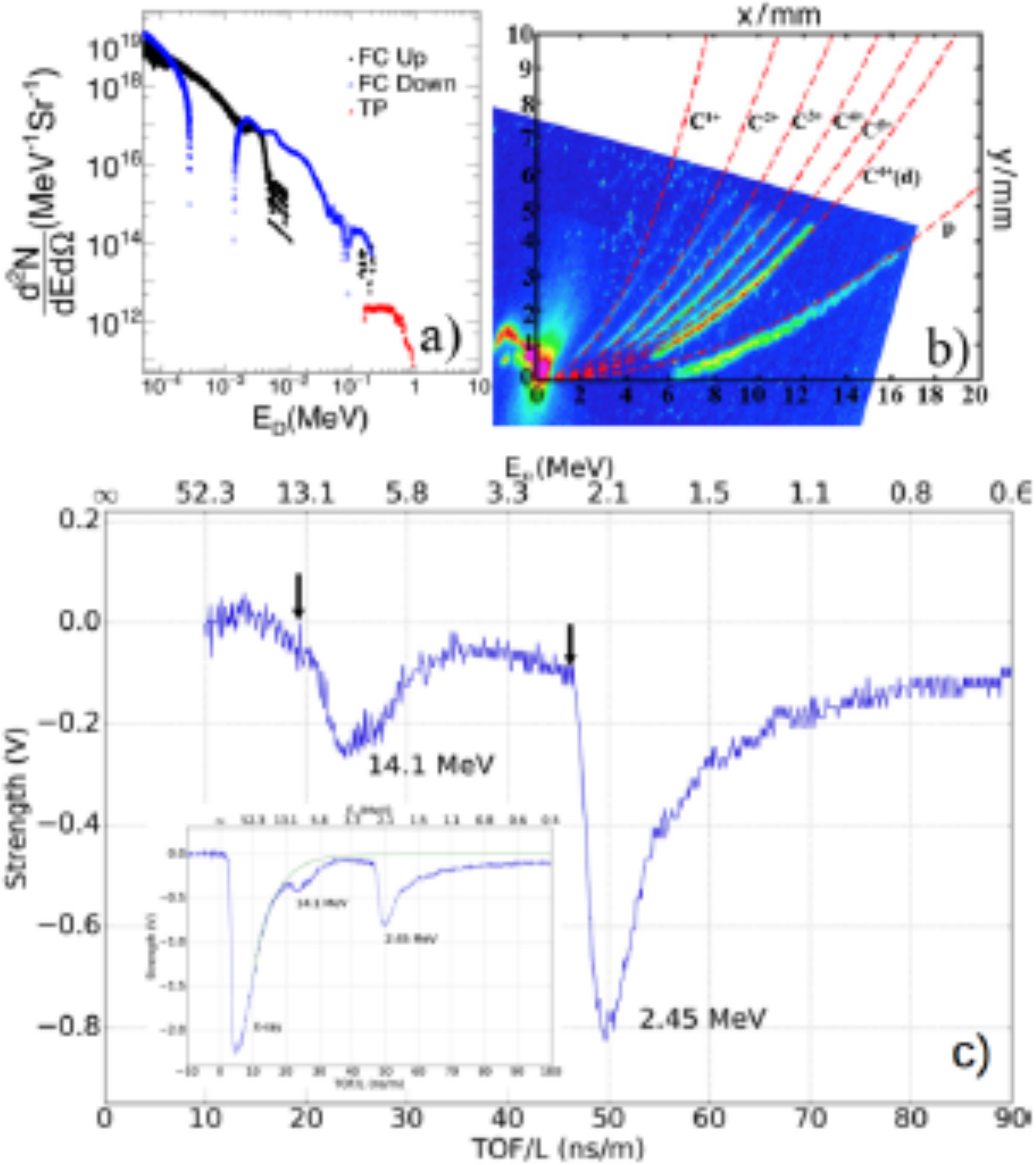


Figure 2: (color online) a) Deuterium energy distribution from the top (full circles) and bottom (open circles) FC, and TP (full triangles). b) TP spectra relative to the laser irradiation of CD_2 target. c) TOF results for 14.1 MeV and 2.45 MeV neutrons from plastic scintillator detector. The two arrows indicate the 14.1 MeV and 2.45 MeV neutron energies.

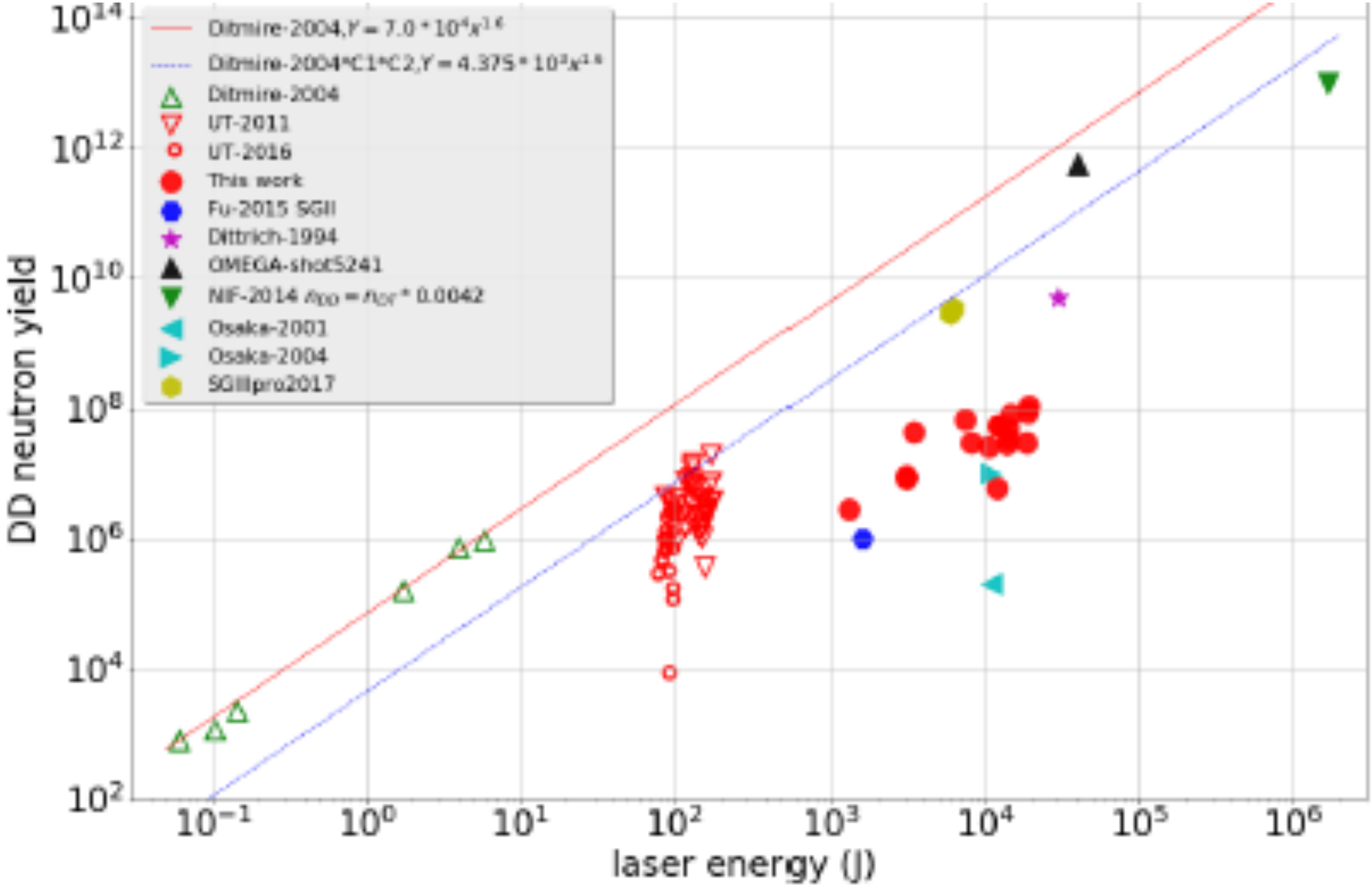


Figure 3: (color online) Fusion yield as function of laser energy. Different experimental results Ditmire-2004[35], UT-2011[20], UT-2016[19], Fu-2015 SGII[40], Dittrich-1994[44] , NIF-2014[43] , Osaka -2001[41], Osaka-2004[42], OMEGA-shot5241[36]and SGIIIpro2017[37] are indicated in the inset.

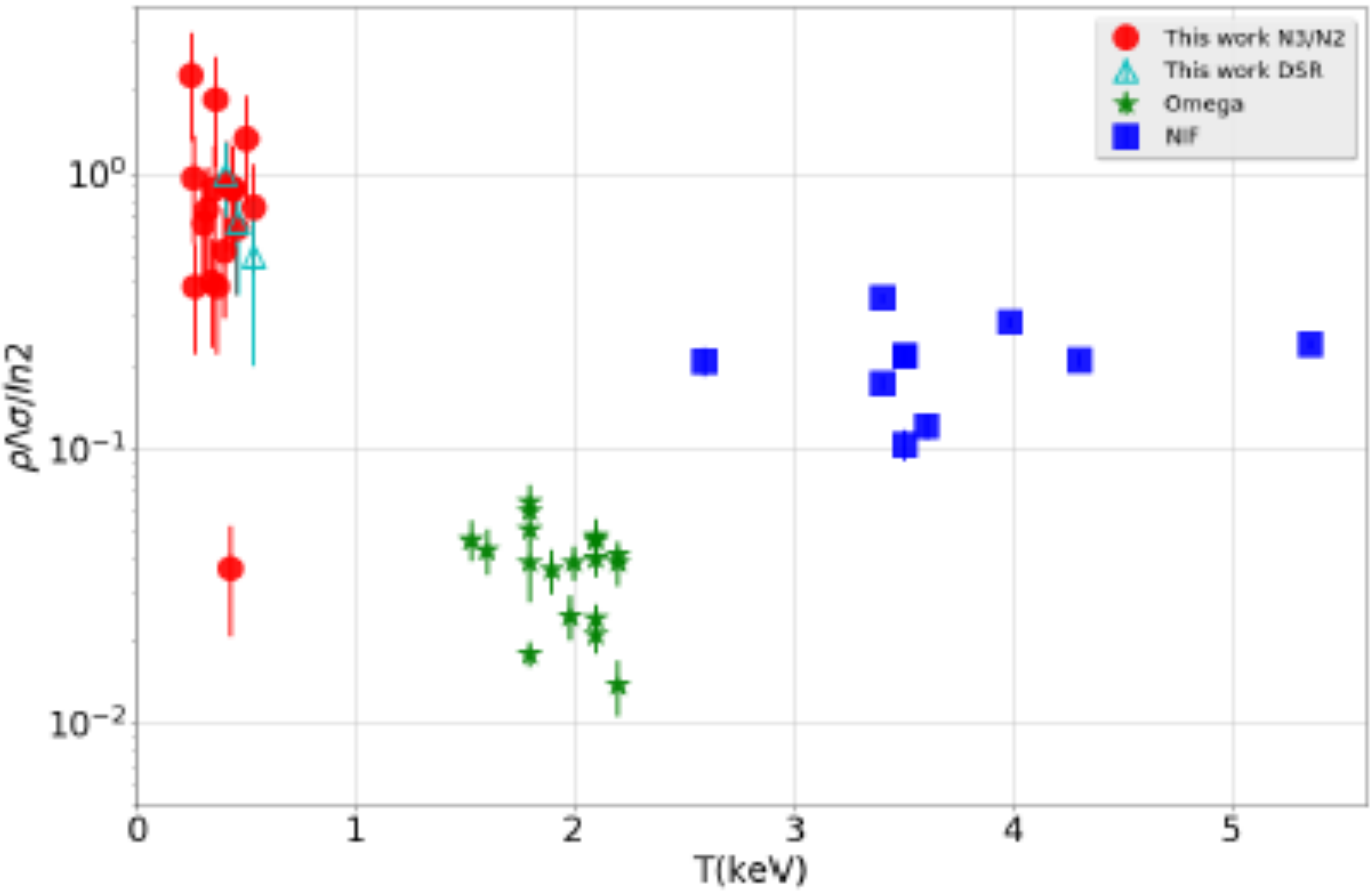


Figure 4: (color online) $\Lambda\rho\sigma/\ln2$ obtained from eq.(4) vs T from eq.(1). Omega and NIF data are derived from the experiments[25], using the Down Scatter Ratio[21,23]. Our results using the DSR method (N4/N3) are given by the open triangle symbols in good agreement with the N3/N2 ratios..

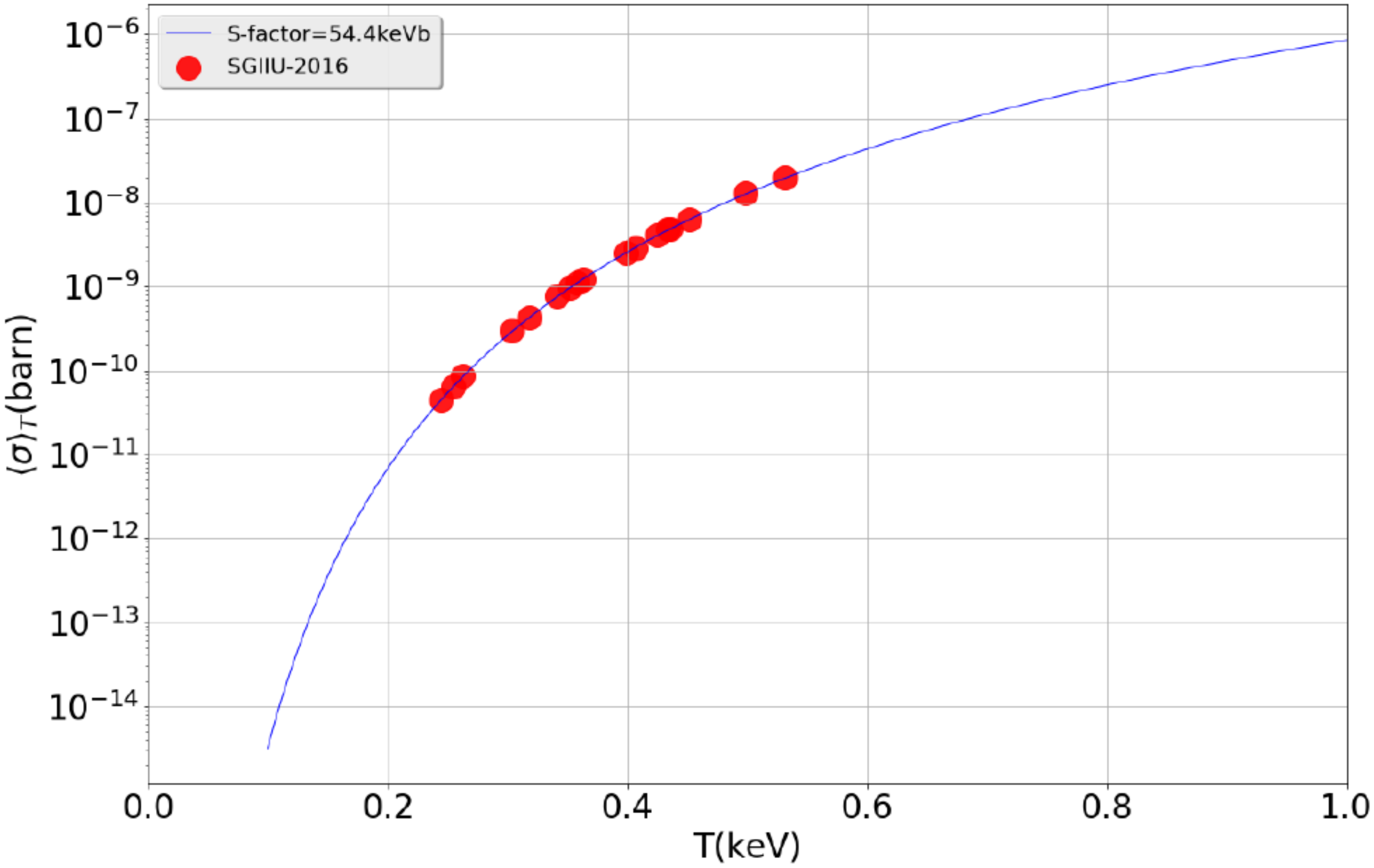


Figure 5: (color online) The average cross section as function of temperature with Maxwell-Boltzmann distribution, expressed by eq. (6) . The red points are the experimental cross section data from eq.(5).

Physics Letters A 383 (2019) 2285–2289

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Nuclear probes of an out-of-equilibrium plasma at the highest compression

G. Zhang [a,b,*], M. Huang [c], A. Bonasera [d,e,*], Y.G. Ma [f,b,i,*], B.F. Shen [g,h,*], H.W. Wang [a,b], W.P. Wang [g], J.C. Xu [g], G.T. Fan [a,b], H.J. Fu [b], H. Xue [b], H. Zheng [j], L.X. Liu [a,b], S. Zhang [c], W.J. Li [b], X.G. Cao [a,b], X.G. Deng [b], X.Y. Li [b], Y.C. Liu [b], Y. Yu [g], Y. Zhang [b], C.B. Fu [k], X.P. Zhang [k]

[a] *Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China*
[b] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*
[c] *College of Physics and Electronics Information, Inner Mongolia University for Nationalities, Tongliao, 028000, China*
[d] *Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA*
[e] *Laboratori Nazionali del Sud, INFN, via Santa Sofia, 62, 95123 Catania, Italy*
[f] *Key Laboratory of Nuclear Physics and Ion-Beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China*
[g] *State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
[h] *Department of Physics, Shanghai Normal University, Shanghai 200234, China*
[i] *University of the Chinese Academy of Sciences, Beijing 100080, China*
[j] *School of Physics and Information Technology, Shaanxi Normal University, Xi'an 710119, China*
[k] *School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*

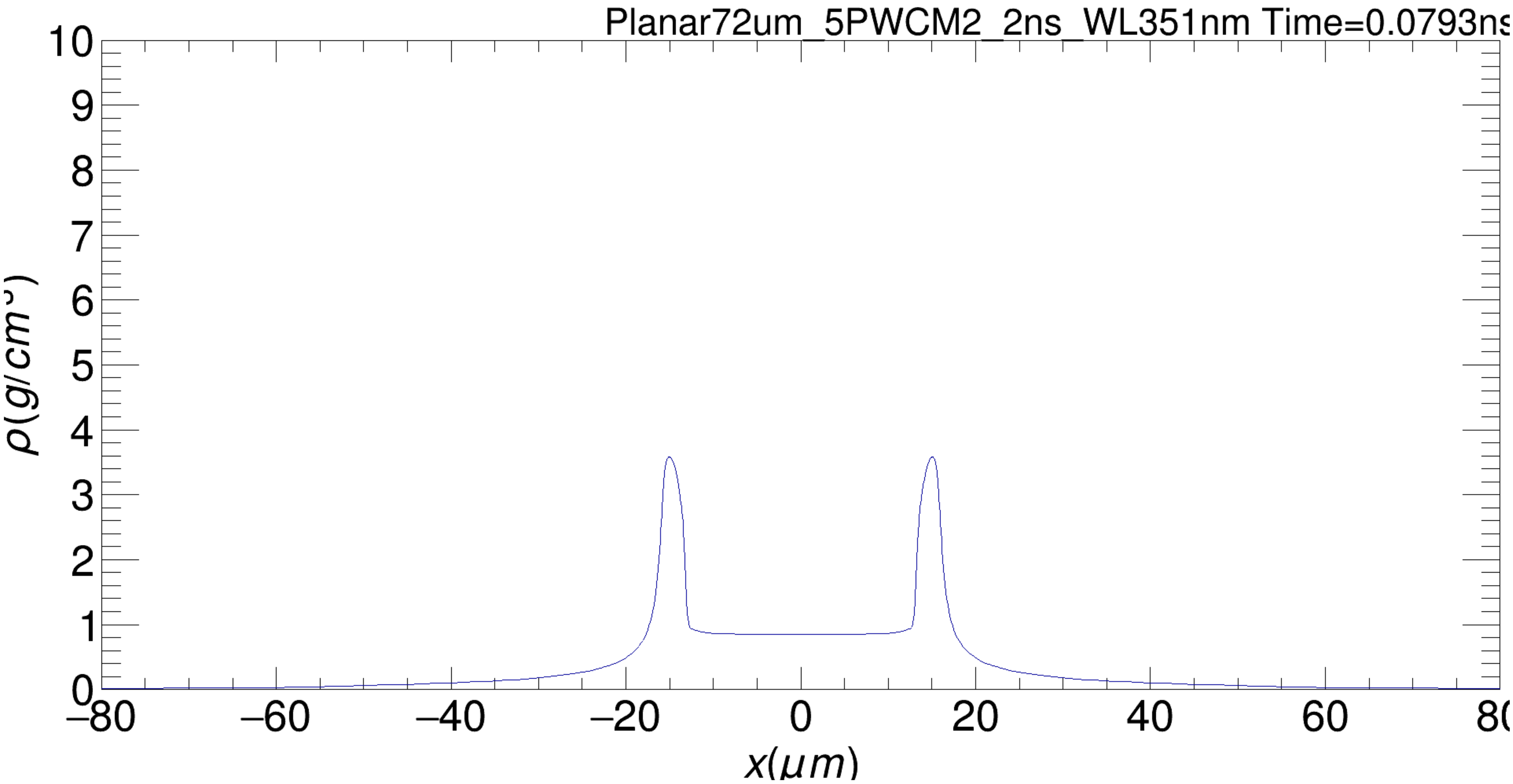
ARTICLE INFO

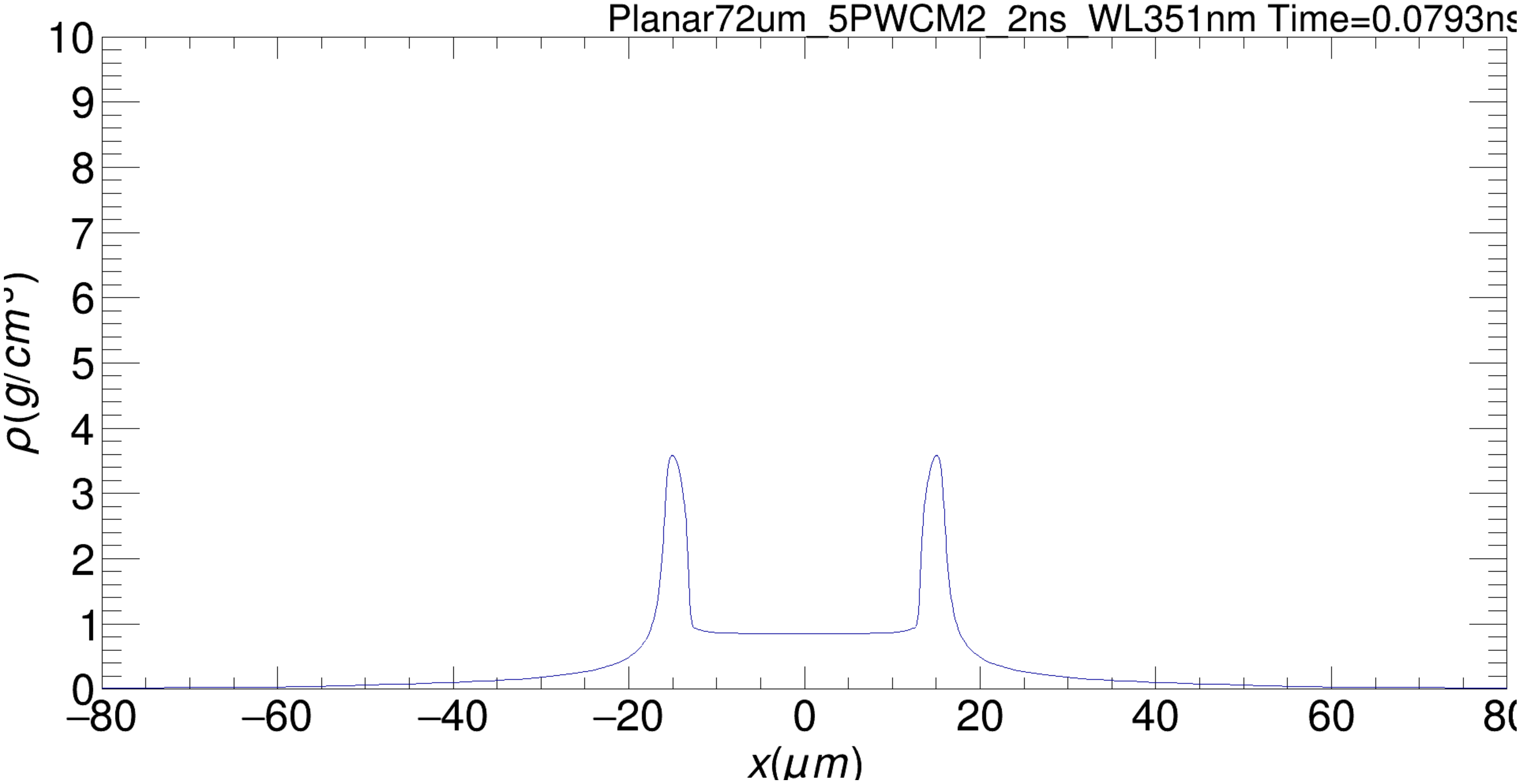
Article history:
Received 16 January 2019
Received in revised form 19 April 2019
Accepted 23 April 2019
Available online 30 April 2019
Communicated by F. Porcelli

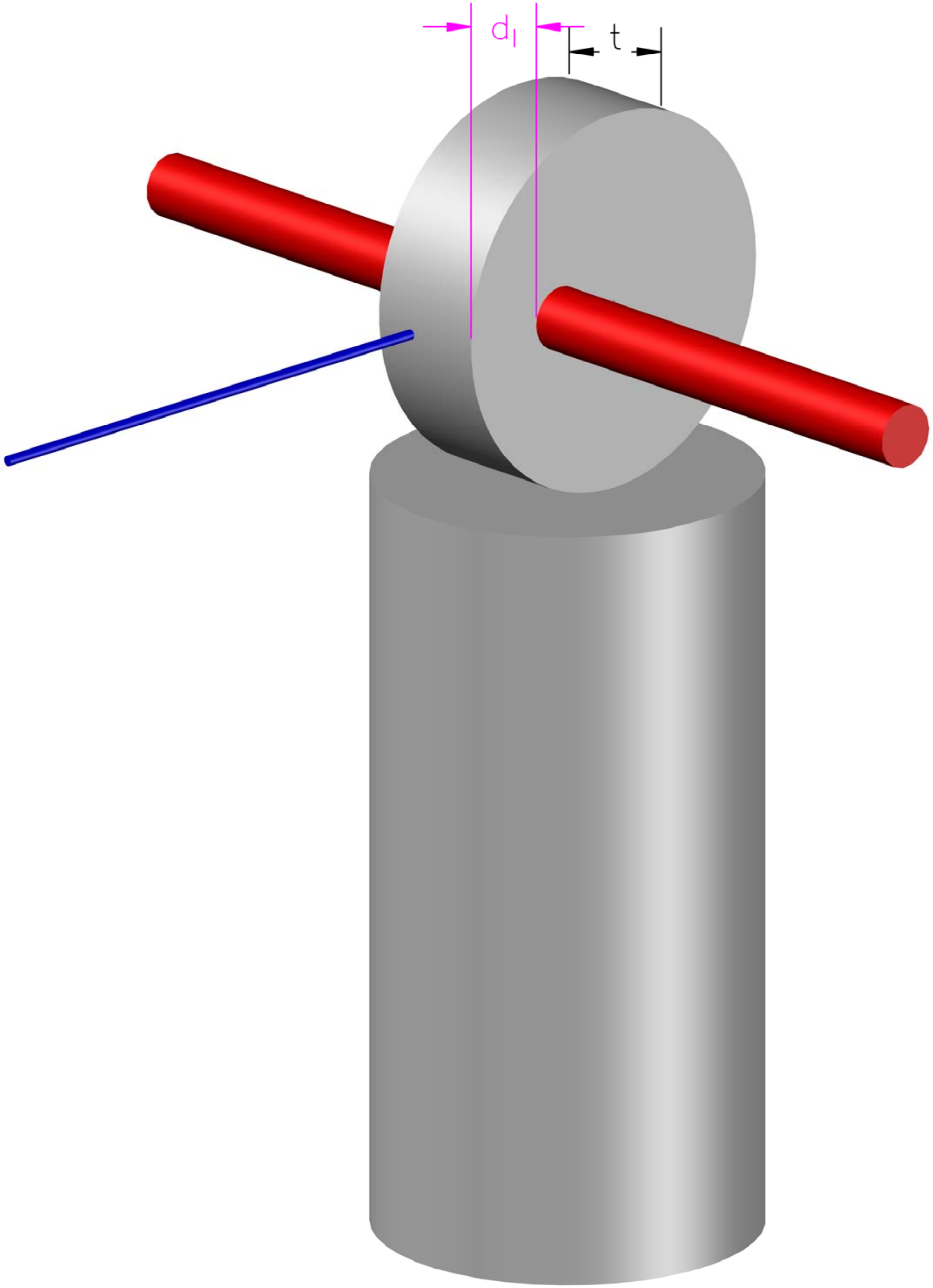
Keywords:
Laser plasma
Nuclear astrophysics
Inertia confinement fusion
High-energy-density plasma

ABSTRACT

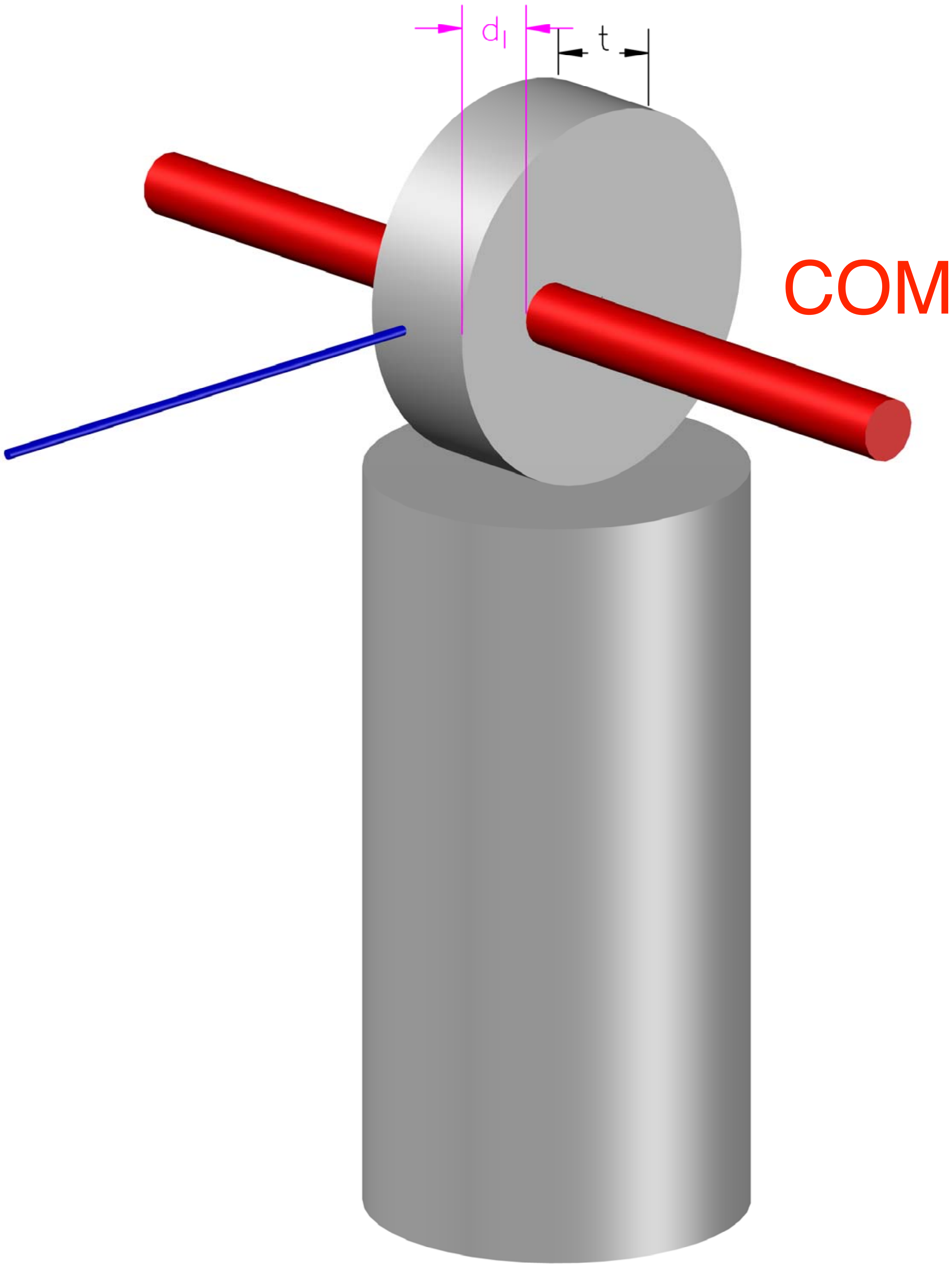
We report the highest compression reached in laboratory plasmas using eight laser beams, $E_{laser} \approx 12$ kJ, $\tau_{laser} = 2$ ns in third harmonic on a CD_2 target at the ShenGuang-II Upgrade (SGII-Up) facility in Shanghai, China. We estimate the deuterium density $\rho_D = 2.0 \pm 0.9$ kg/cm^3, and the average kinetic energy of the plasma ions less than 1 keV. The highest reached areal density $\Lambda\rho_D = 4.8 \pm 1.5$ g/cm^2 was obtained from the measured ratio of the sequential ternary fusion reactions (dd$\rightarrow$t+p and t+d$\rightarrow\alpha$+n) and the two body reaction fusions (dd $\rightarrow {}^3$He + n). At such high densities, sequential ternary and also quaternary nuclear reactions become important as well (i.e. n(14.1 MeV)+^{12}C $\rightarrow$ n'+^{12}C* etc.) resulting in a shift of the neutron (and proton) kinetic energies from their birth values. The Down Scatter Ratio (DSR-quaternary nuclear reactions) method, i.e. the ratio of the 10-12 MeV neutrons divided by the total number of 14.1 MeV neutrons produced, confirms the high densities reported above. The estimated lifetime of the highly compressed plasma is 52 ± 9 ps, much smaller than the lasers pulse duration.


Planar72um_5PWCM2_2ns_WL351nm Time=0.0793ns
$\rho(g/cm^3)$
0
1
2
3
4
5
6
7
8
9
10
–80
–60
–40
–20
0
20
40
60
80
$x(\mu m)$

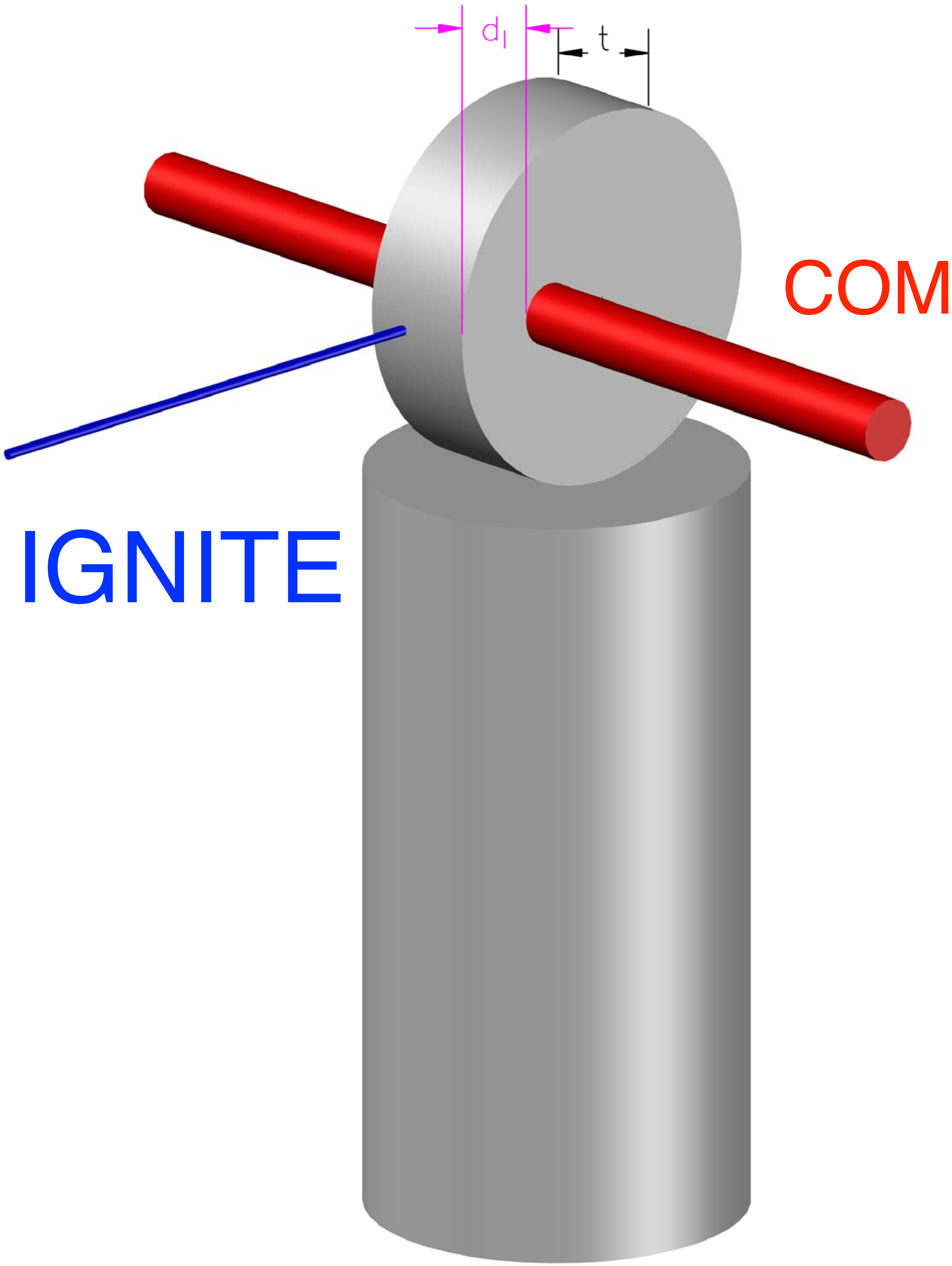

Planar72um_5PWCM2_2ns_WL351nm Time=0.0793ns
ρ(g/cm³)
10
9
8
7
6
5
4
3
2
1
0
−80
−60
−40
−20
0
20
40
60
80
x(μm)



d_l
t

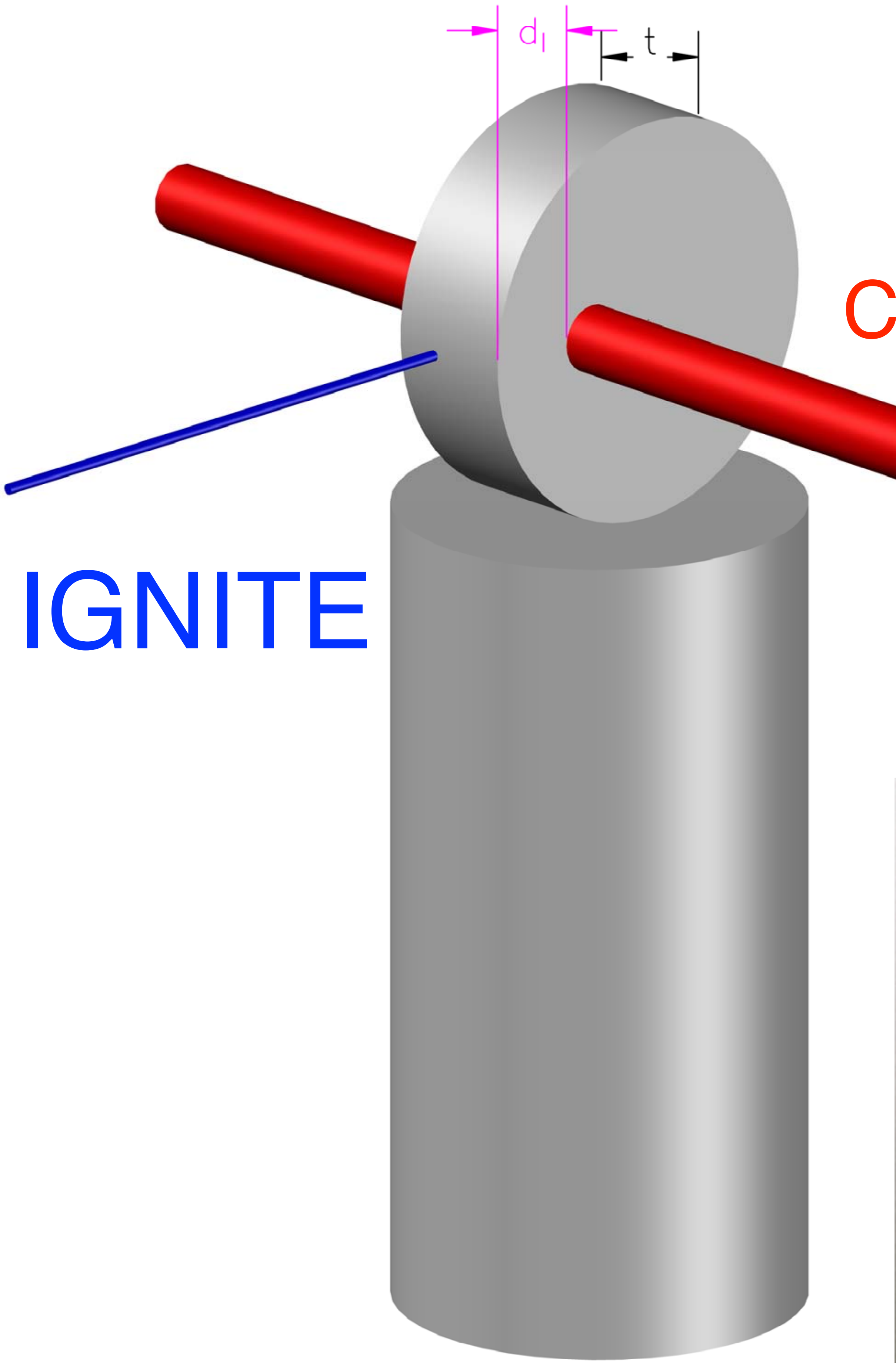


COMPRESS



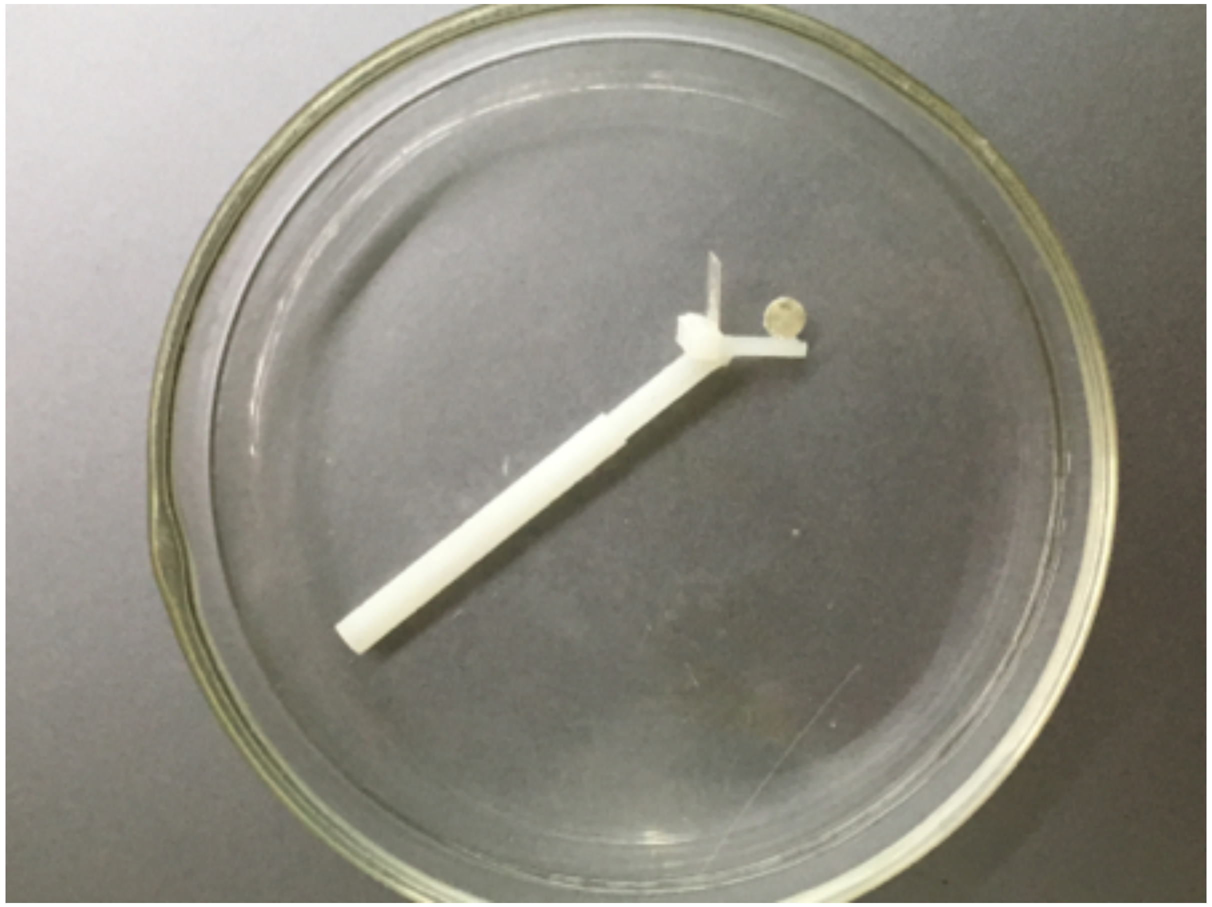
COMPRESS

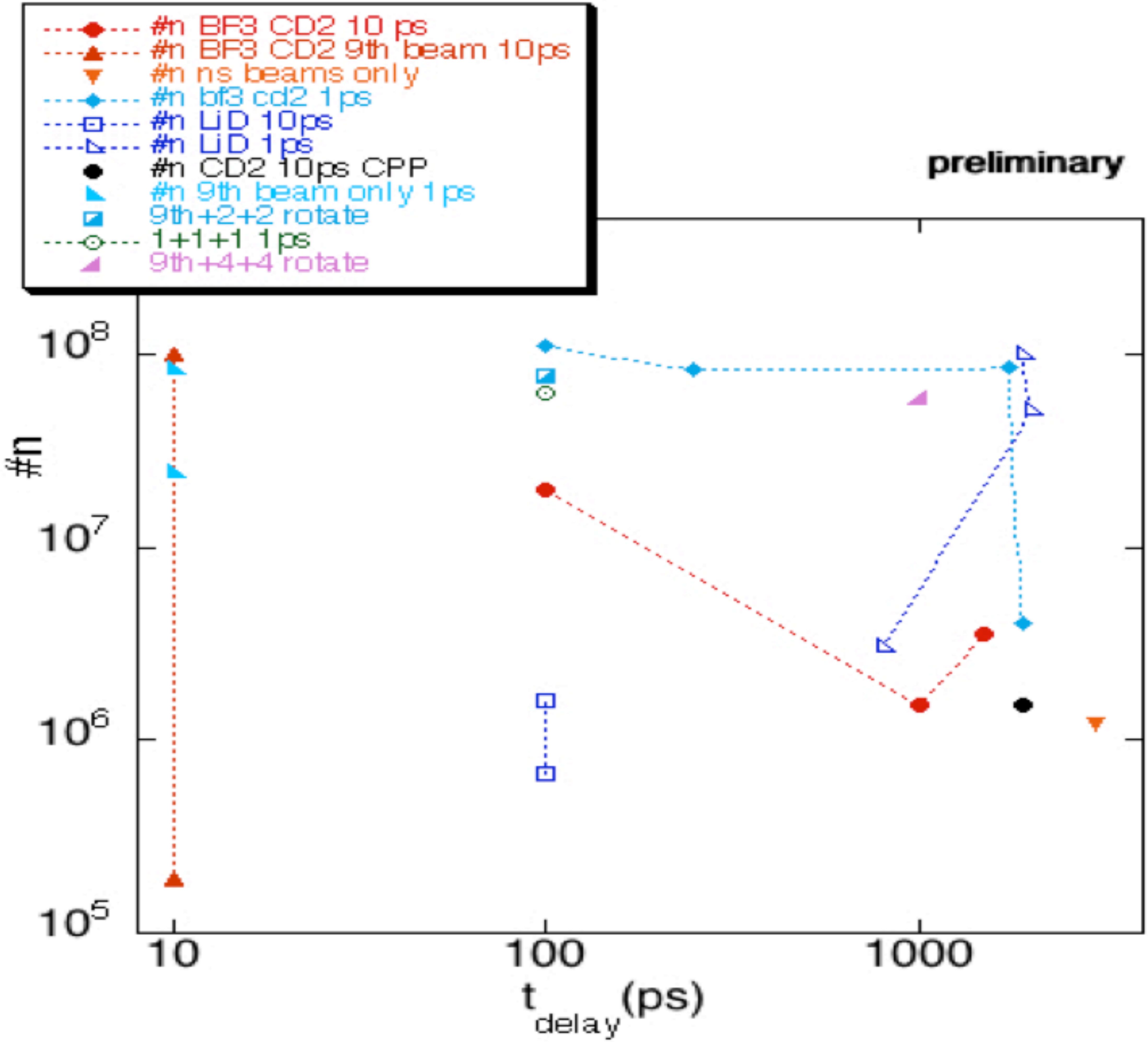
IGNITE



COMPRESS

IGNITE





preliminary

Nuclear Physics News
International

Nuclear Astrophysics with Lasers

Meirong Huang, Hernan J. Quevedo, Guoqiang Zhang & Aldo Bonasera

A systematic program of investigations of nuclear reactions in laser-produced plasmas is addressed. Such reactions provide an important diagnostic tool for probing the dynamics and thermodynamics in the plasma and understanding laser ion acceleration and neutron production mechanisms. The goal will be to reach the level of knowledge that allows the measurement of fundamental nuclear cross sections at low and high particle densities. The quantitative measurement of fusion probabilities in hot and dense plasmas will contribute significantly to our comprehension of stellar composition and evolution and will provide important information for development of fusion energy production and applications such as medical isotope production and compact neutron source development. All of these are some of the main goals of the European Extreme Light Infrastructure (ELI), the Shanghai Superintense Ultrafast Laser Facility (SULF), the Station of Extreme Light (SEL) in China and similar projects in other countries.

Work in collaboration with:

Work in collaboration with:

Fabrizio Consoli [a,*], Riccardo De Angelis [a], Pierluigi Andreoli [a], Giuseppe Cristofari [a],
Giorgio Di Giorgio [a], Aldo Bonasera [b,c], Marina Barbui [c], Marco Mazzocco [d], Woosuk Ban
Gilliss Dyer [e], Hernan Quevedo [e], Kris Hagel [c], Katarzyna Schmidt [c], Erhard Gaul [e],
Ted Borger [e], Aaron Bernstein [e], Mikael Martinez [e], Michael Donovan [e], Matteo Barbarin
Sachie Kimura [b], Jozef Sura [f], Joseph Natowitz [c], Todd Ditmire [e]

[a] *Associazione Euratom - ENEA sulla Fusione, via E. Fermi 45, CP 65-00044 Frascati, Rome, Italy*
[b] *INFN - LNS, via S. Sofia 62, I-95123 Catania, Italy*
[c] *Cyclotron Institute, Texas A&M University, College Station, TX, 77843, USA*
[d] *Dipartimento di Fisica G. Galilei, Università degli Studi di Padova, via F. Marzolo 8, I-35131 Padova, Italy*
[e] *Texas Center for High Intensity Laser Science, University of Texas at Austin, Austin 78712, TX, USA*
[f] *Heavy Ions Laboratory, University of Warsaw, ul. Pasteura 5a, 02-093 Warszawa, Poland*

Work in collaboration with:

Fabrizio Consoli[a,*], Riccardo De Angelis[a], Pierluigi Andreoli[a], Giuseppe Cristofari[a],
Giorgio Di Giorgio[a], Aldo Bonasera[b,c], Marina Barbui[c], Marco Mazzocco[d], Woosuk Ban
Gilliss Dyer[e], Hernan Quevedo[e], Kris Hagel[c], Katarzyna Schmidt[c], Erhard Gaul[e],
Ted Borger[e], Aaron Bernstein[e], Mikael Martinez[e], Michael Donovan[e], Matteo Barbarin
Sachie Kimura[b], Jozef Sura[f], Joseph Natowitz[c], Todd Ditmire[e]

CENTER OF EXCELLENCE

CENTAUR

IN NUCLEAR TRAINING AND UNIVERSITY-BASED RESEARCH

CENTER OF EXCELLENCE
CENTAUR
IN NUCLEAR TRAINING AND UNIVERSITY-BASED RESEARCH

Thank you !