Using lasers for Nuclear Physics: measuring cross-sections in (non) equilibrium plasmas

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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.

Progress of Theoretical Physics Supplement No. 154, 2004

Dynamics of Fusion in Plasmas

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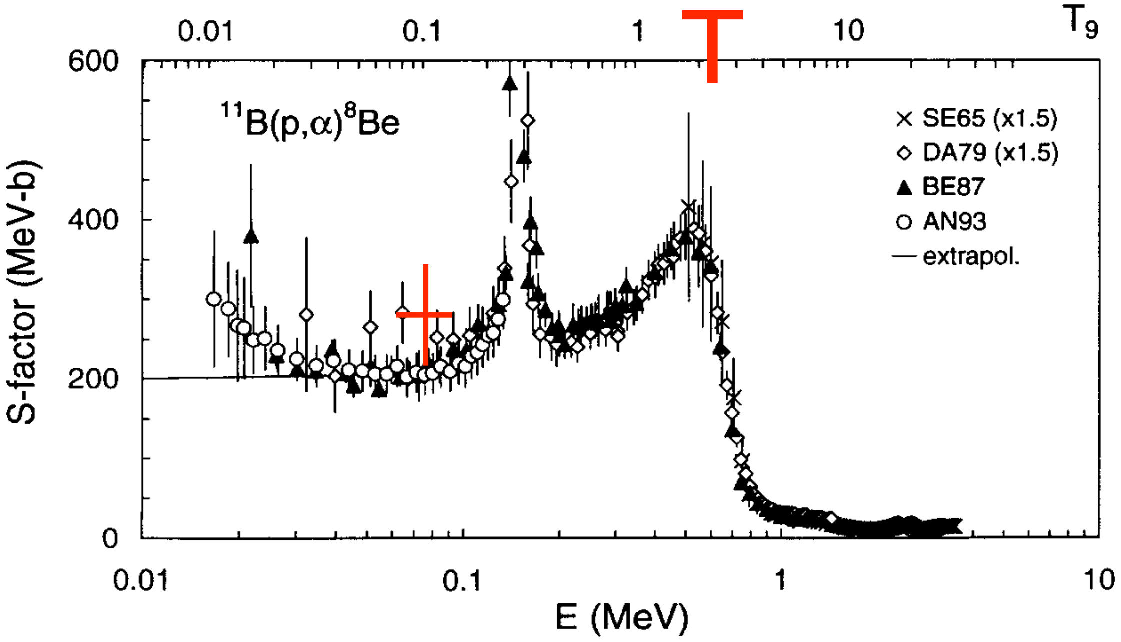
We investigate the possibility of gaining energy from nuclear fusion reactions using different mixtures of D, T and ^{6}Li. First, a plasma in equilibrium is studied at different densities and temperatures. In a second, highly non equilibrium case, the plasma is at high densities and excitation energies. While the first case could lead to an energy gain especially when coupled to an accelerator, in the second case the energy given to the system might be larger than the output energy even for a D+T plasma. This is due to the small number of particles which can be treated numerically. Furthermore, there is a possible double counting between the elementary fusion cross section and the exact Coulomb potential used in the calculations.

Measuring S-factors in hot and dense plasma

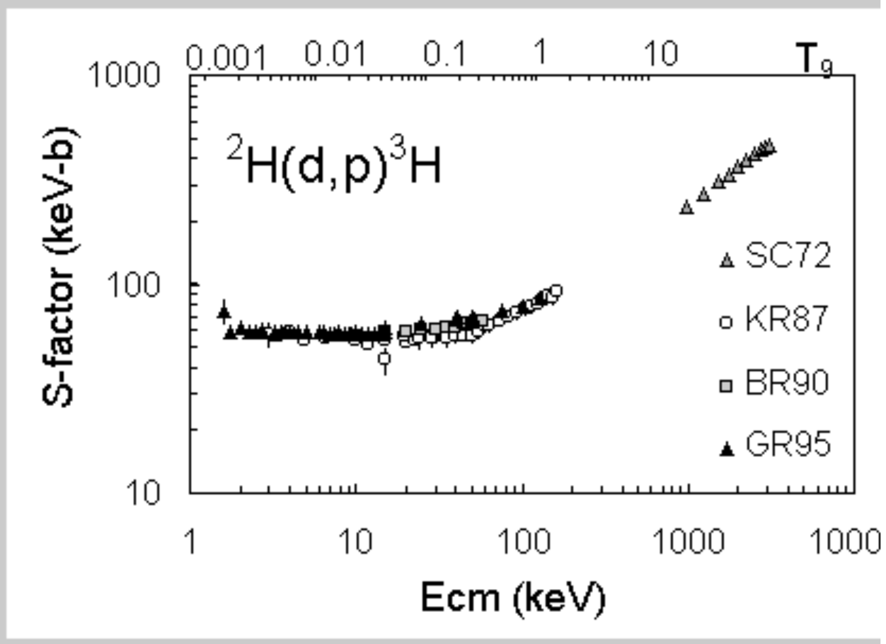
$N = \iint dV\, dt\, n_1 n_2 \langle \sigma_{12} v \rangle,$

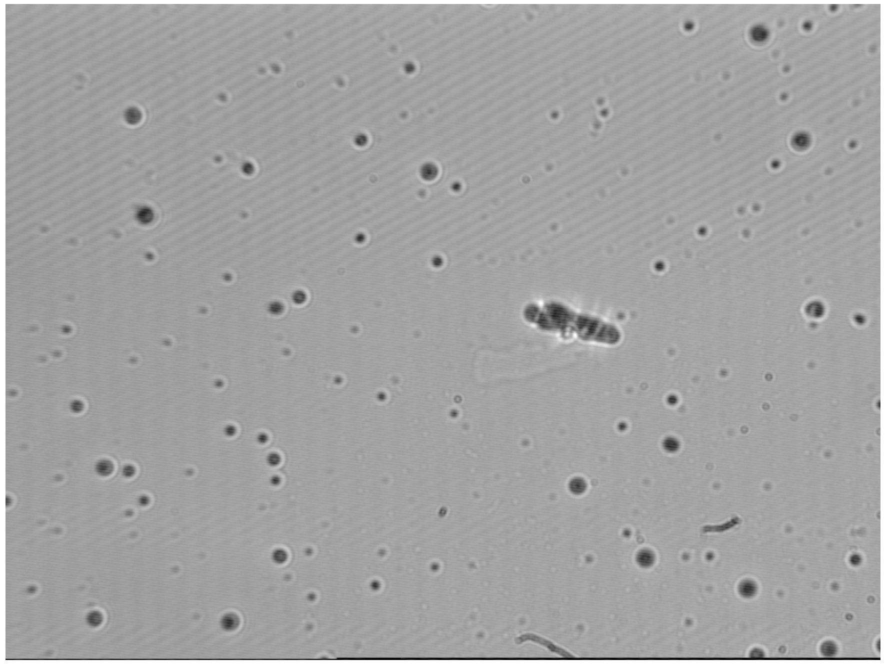
Measure the number of fusion N, the plasma phase space densities (i.e. T) n1,n2 (e.g. p+B) and volumes then recover the cross-section (or S-factor)

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



Add a third axis:density!





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

User Experimental Proposal

For Consideration

Texas Petawatt Laser Facility

Center for High Energy Density Science
Dept. of Physics, The University of Texas at Austin
Austin, TX 78712

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)
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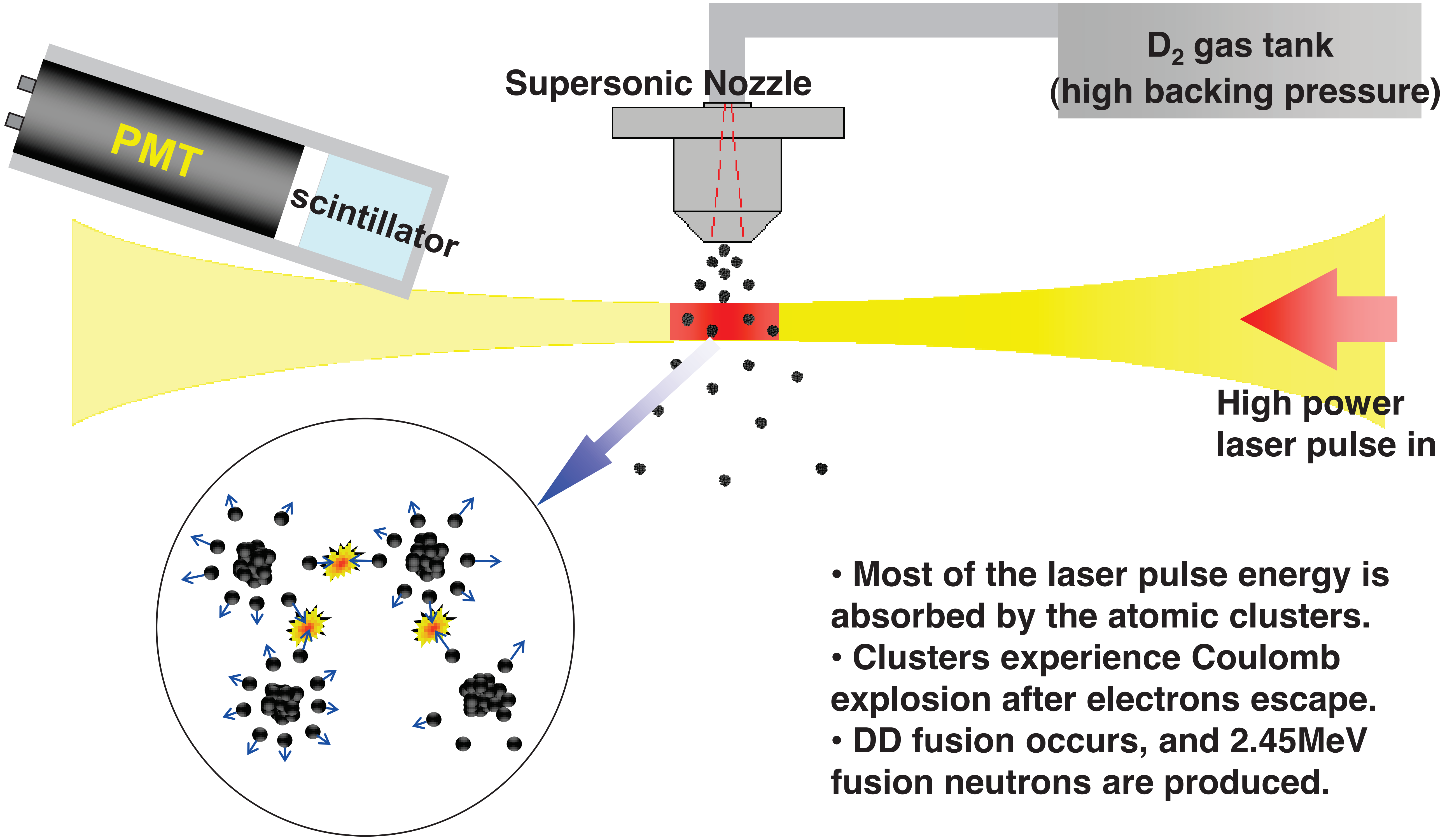
P.Andreoli, R.DeAngelis, F.Consoli, ENEA

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:

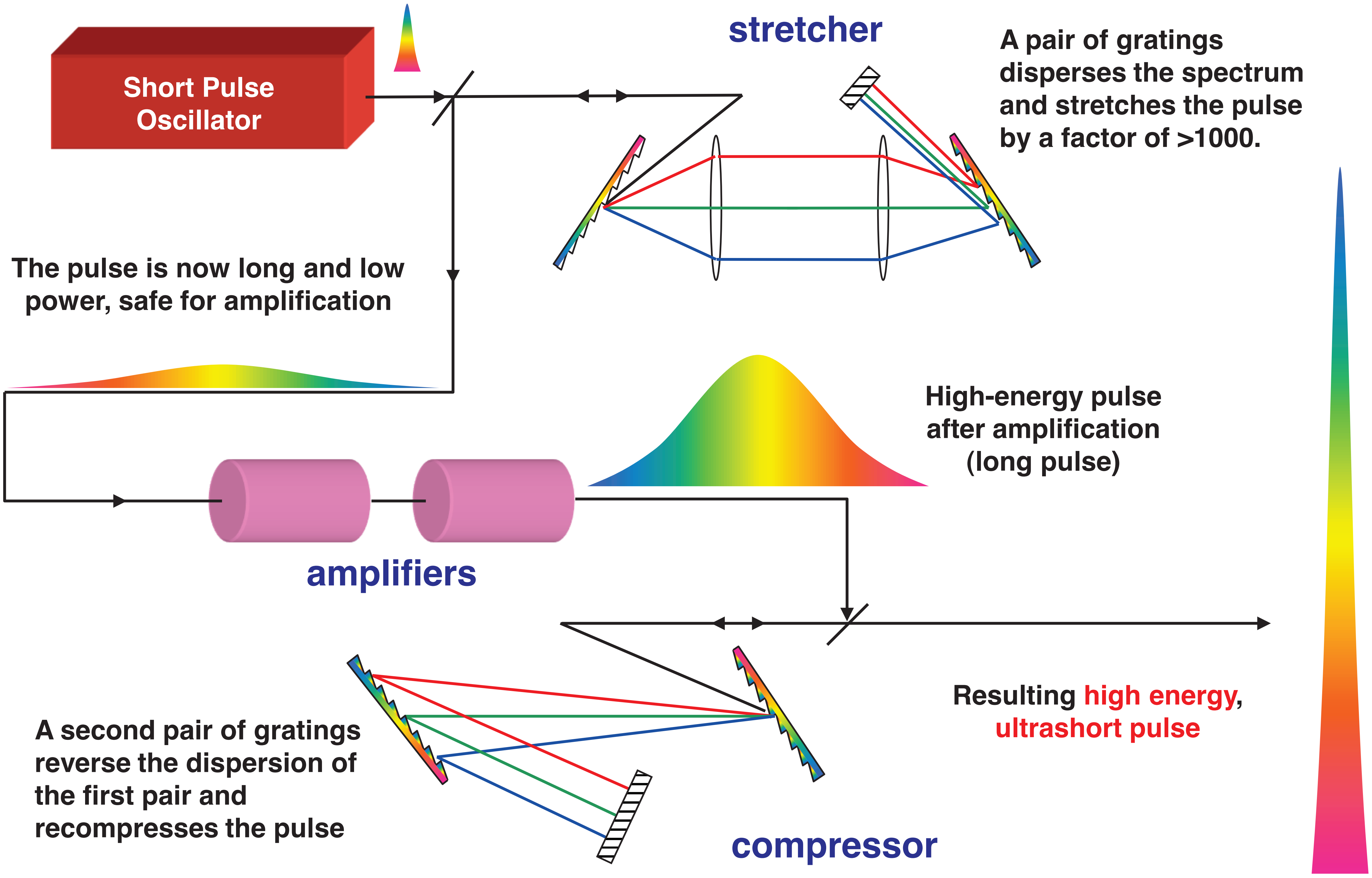
D + D ->T (1.01 MeV) + p (3.02 MeV) (50%)

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%)

Chirped Pulse Amplification (CPA) is the basic technique for modern ultra-intense, ultrafast lasers



Short Pulse Oscillator

stretcher

A pair of gratings disperses the spectrum and stretches the pulse by a factor of >1000.

The pulse is now long and low power, safe for amplification

High-energy pulse after amplification (long pulse)

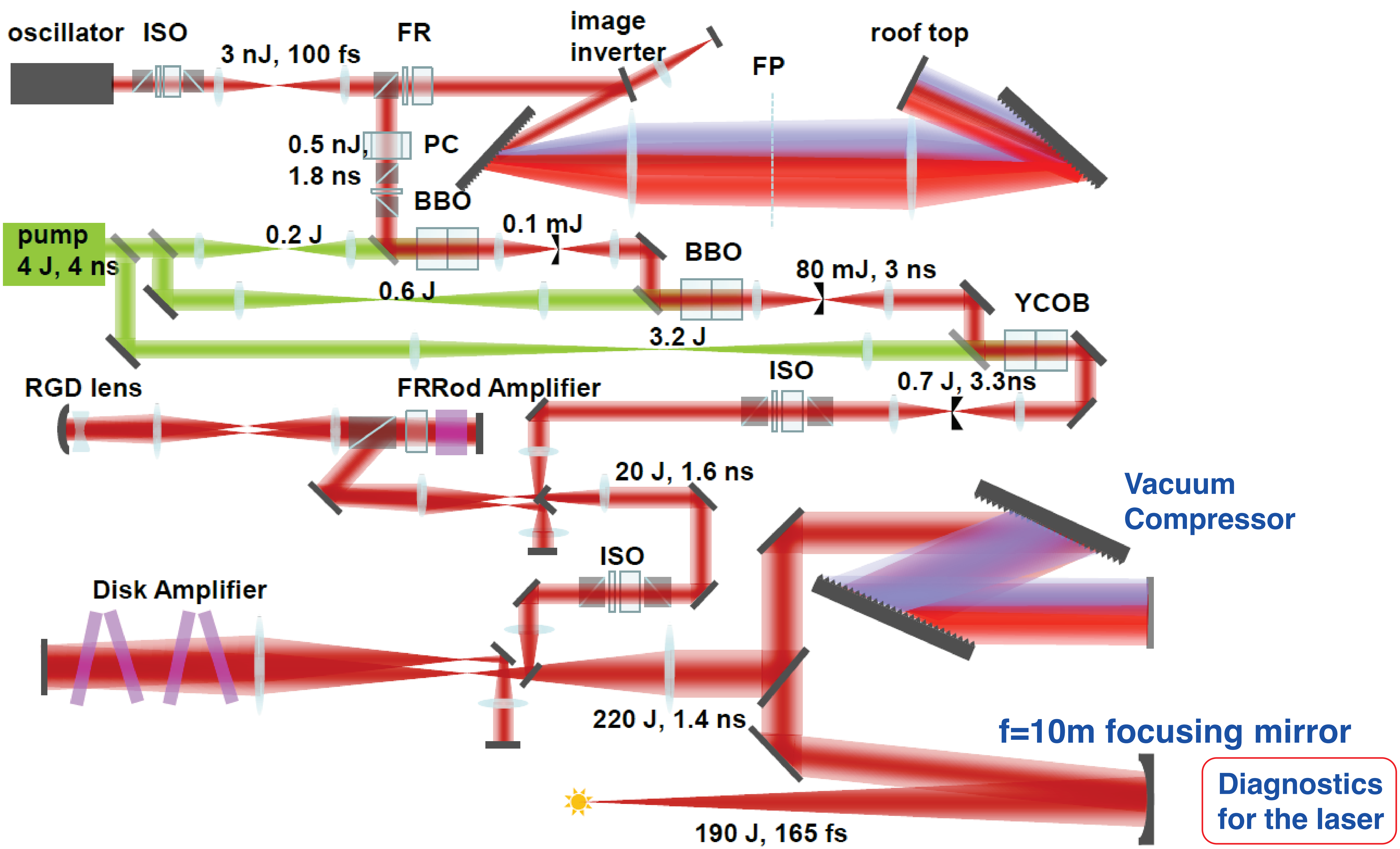
amplifiers

Resulting high energy, ultrashort pulse

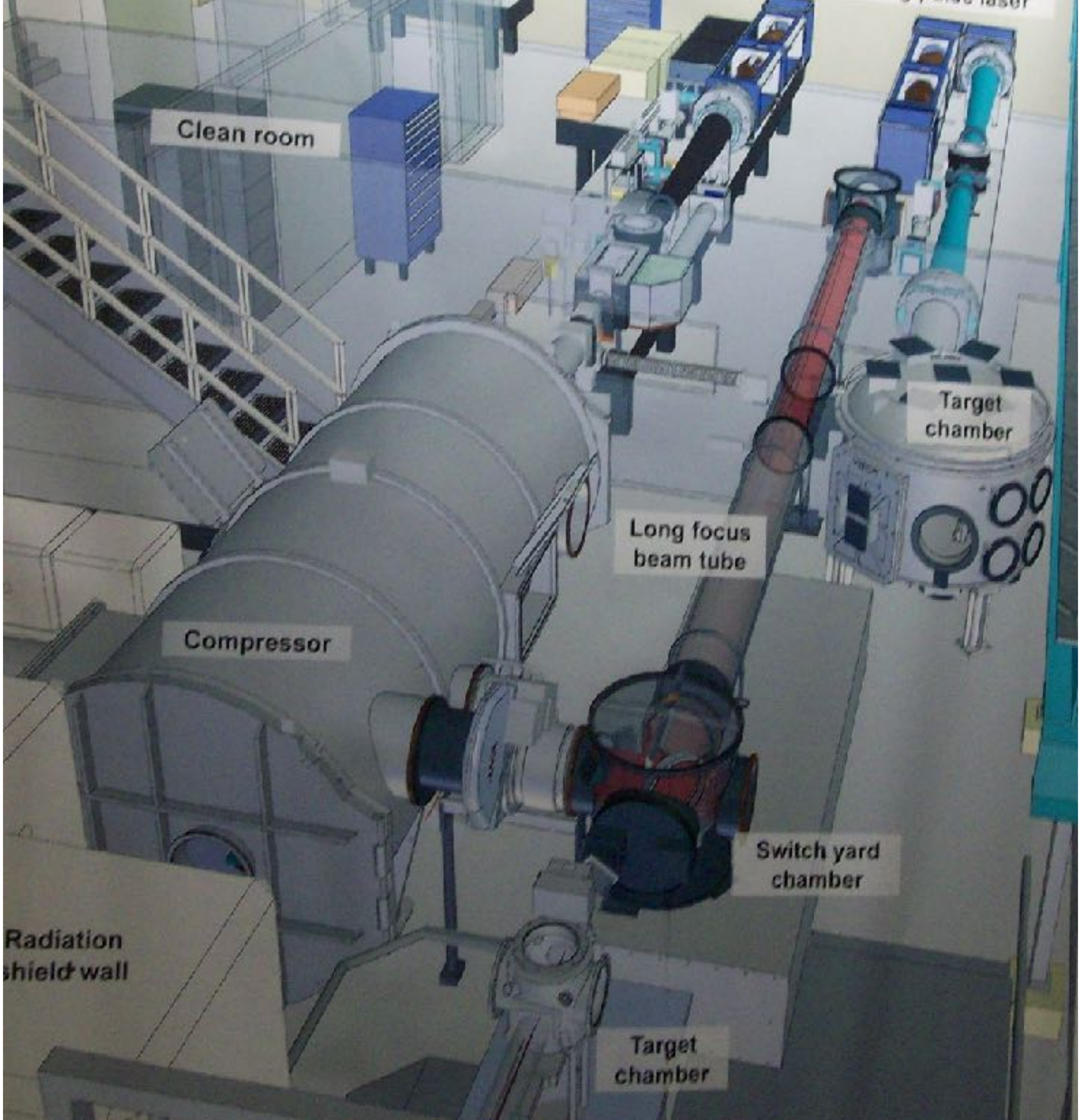
A second pair of gratings reverse the dispersion of the first pair and recompresses the pulse

compressor

Texas Petawatt laser uses three OPCPA and two Nd:glass amplifier stages and delivers a 190J laser pulse

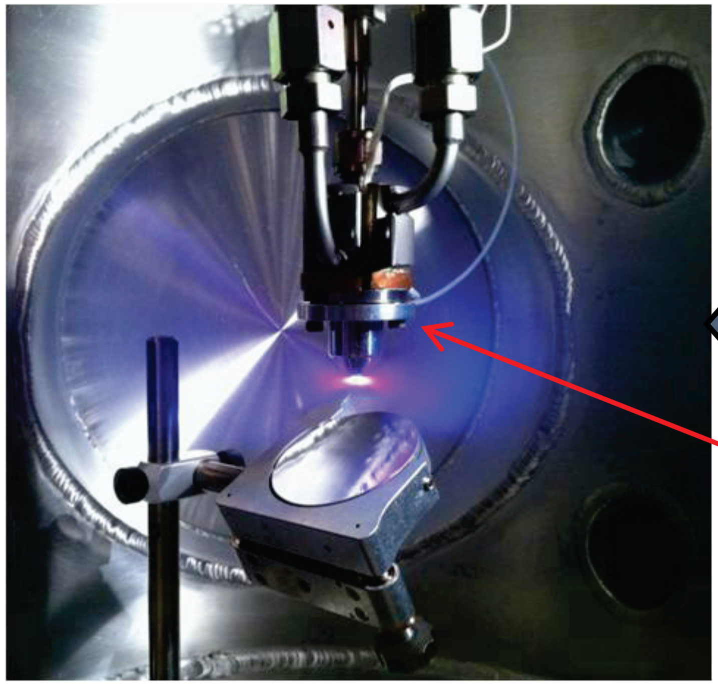


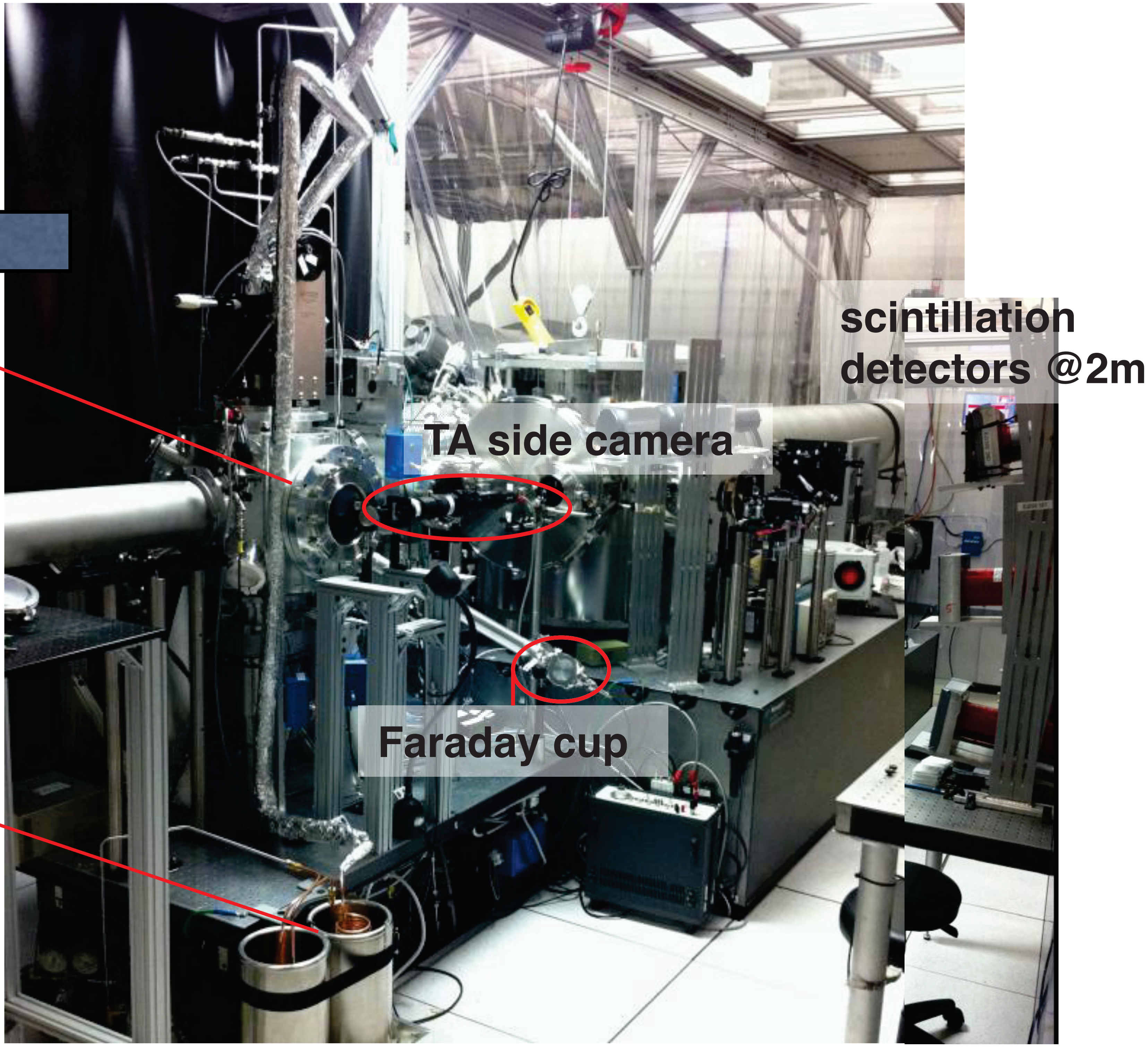
Diagnostics for the laser

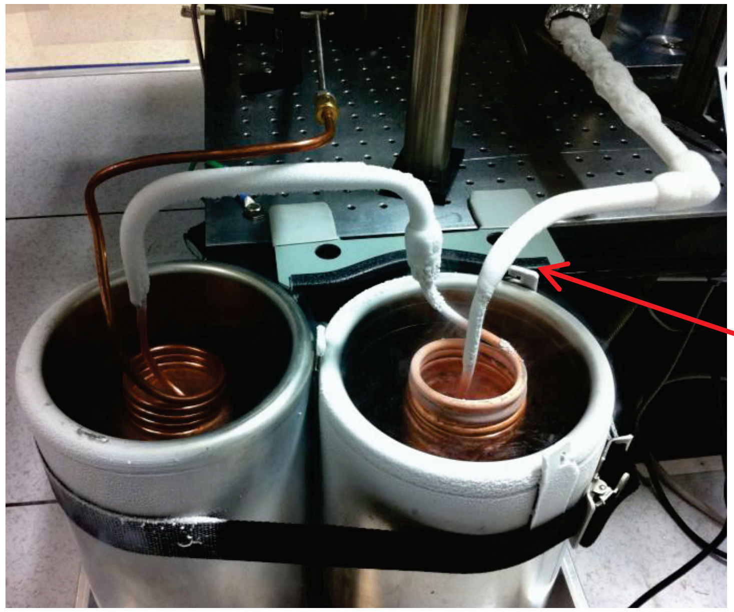

Clean room
Target chamber
Long focus beam tube
Compressor
Switch yard chamber
Radiation shield wall
Target chamber

fusion experiments on the Texas Petawatt

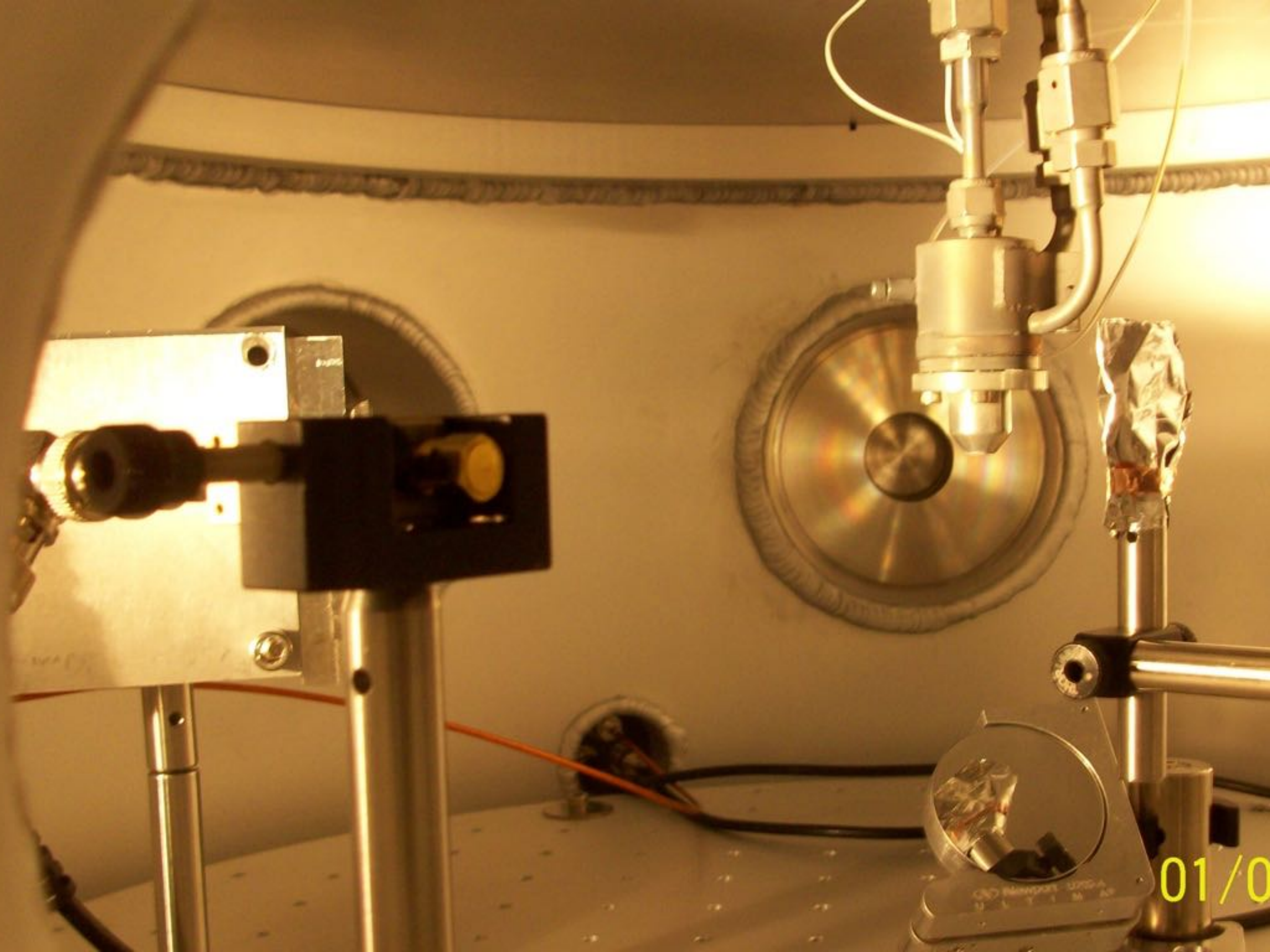
Target area of the Texas Petawatt for the cluster fusion experiment







LN2 cooling line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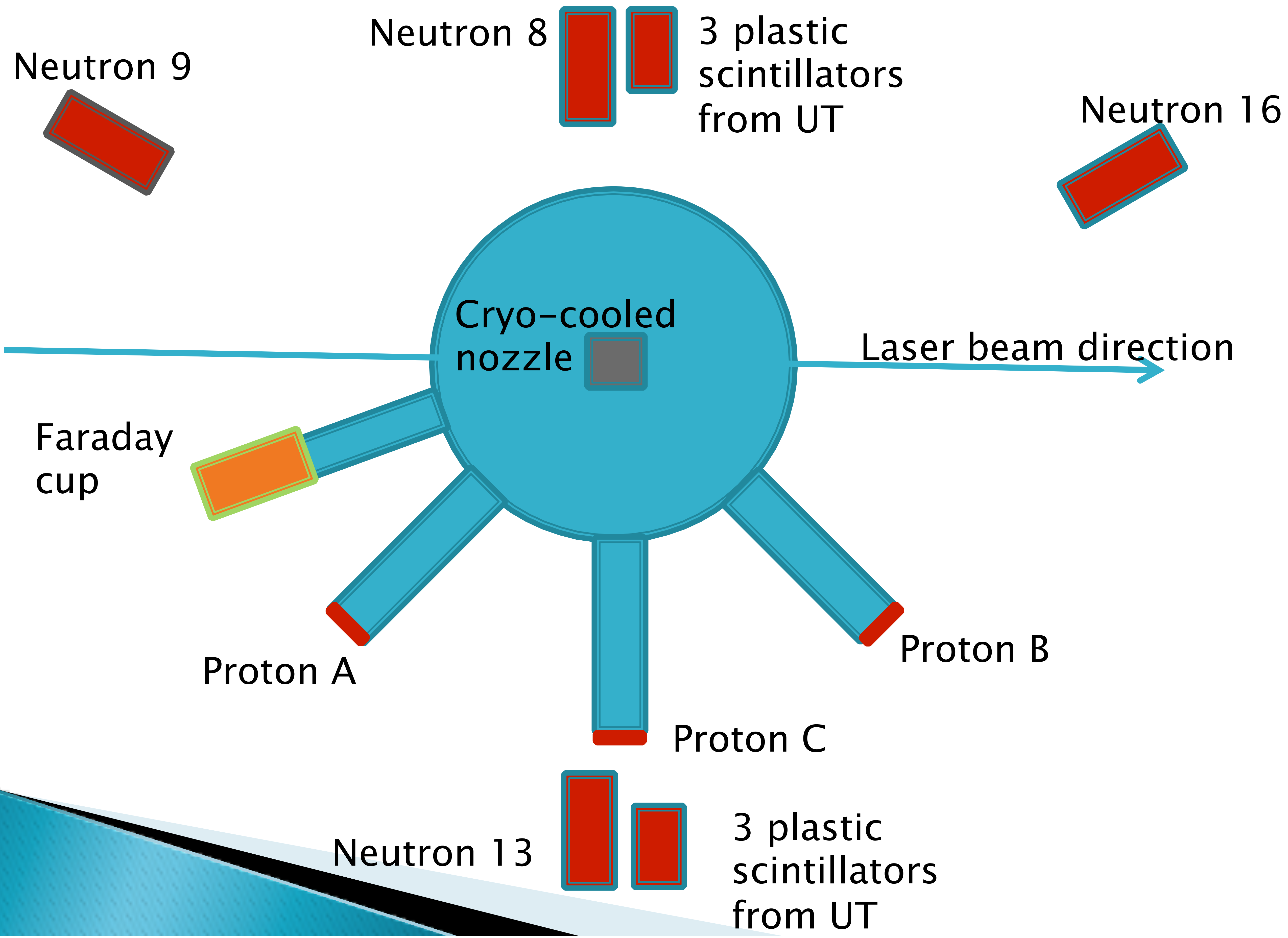
Experimental setup



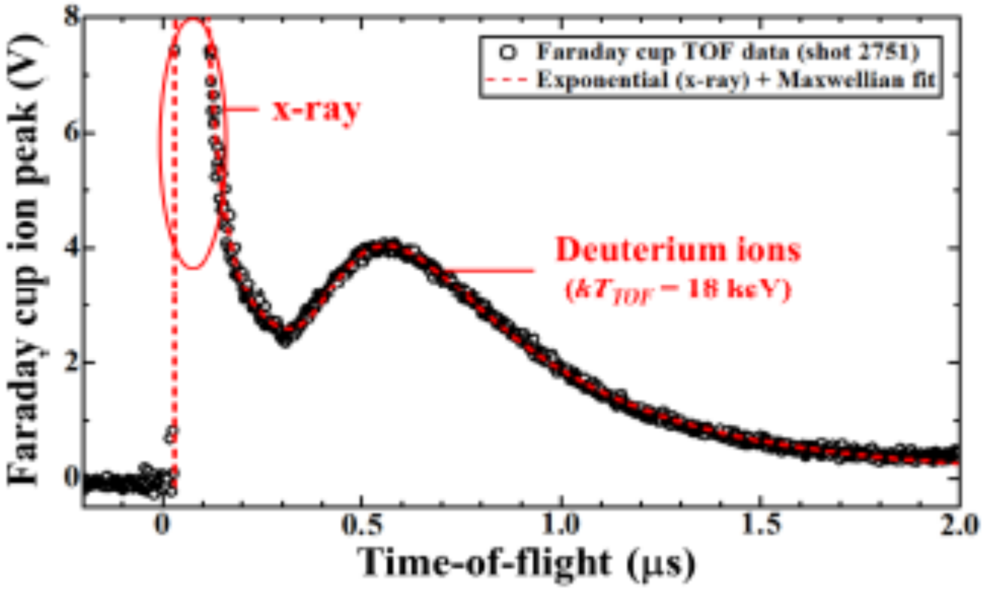
Measure V for each event

Measured observables

Measure N. of ions

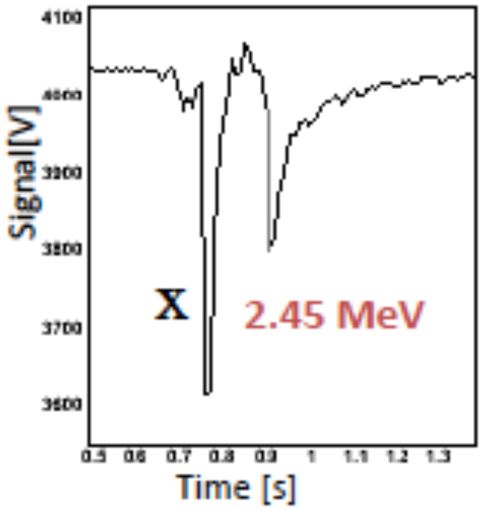
Temperature and the number of the energetic ions

Faraday cup



Yield of 2.45 MeV neutrons

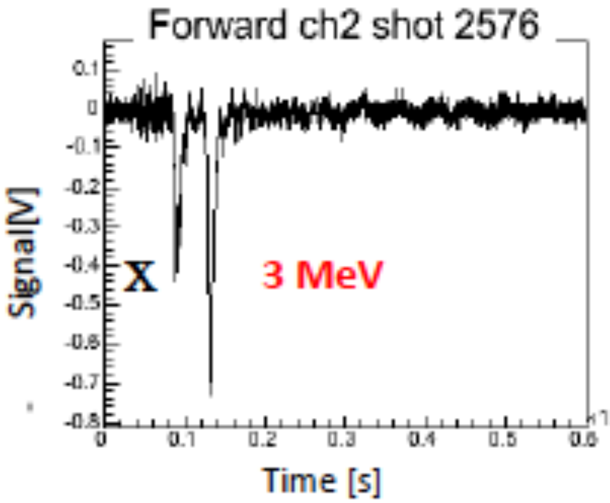
4 liquid scintillators NE213 placed at different angles and 6 plastic scintillators placed at 90 degrees

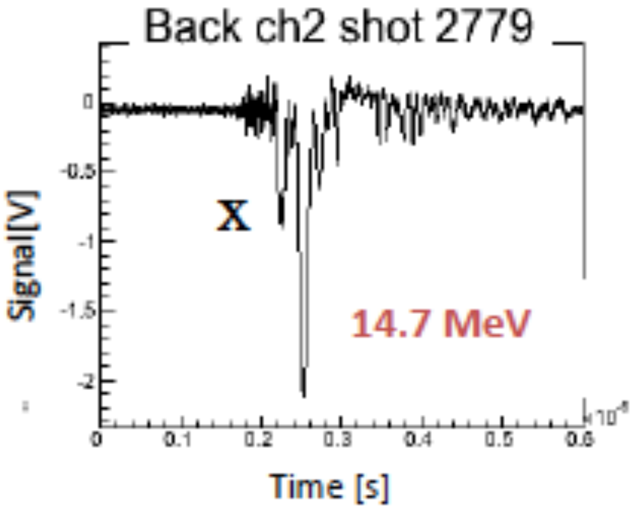


Yield of 3.02 MeV protons

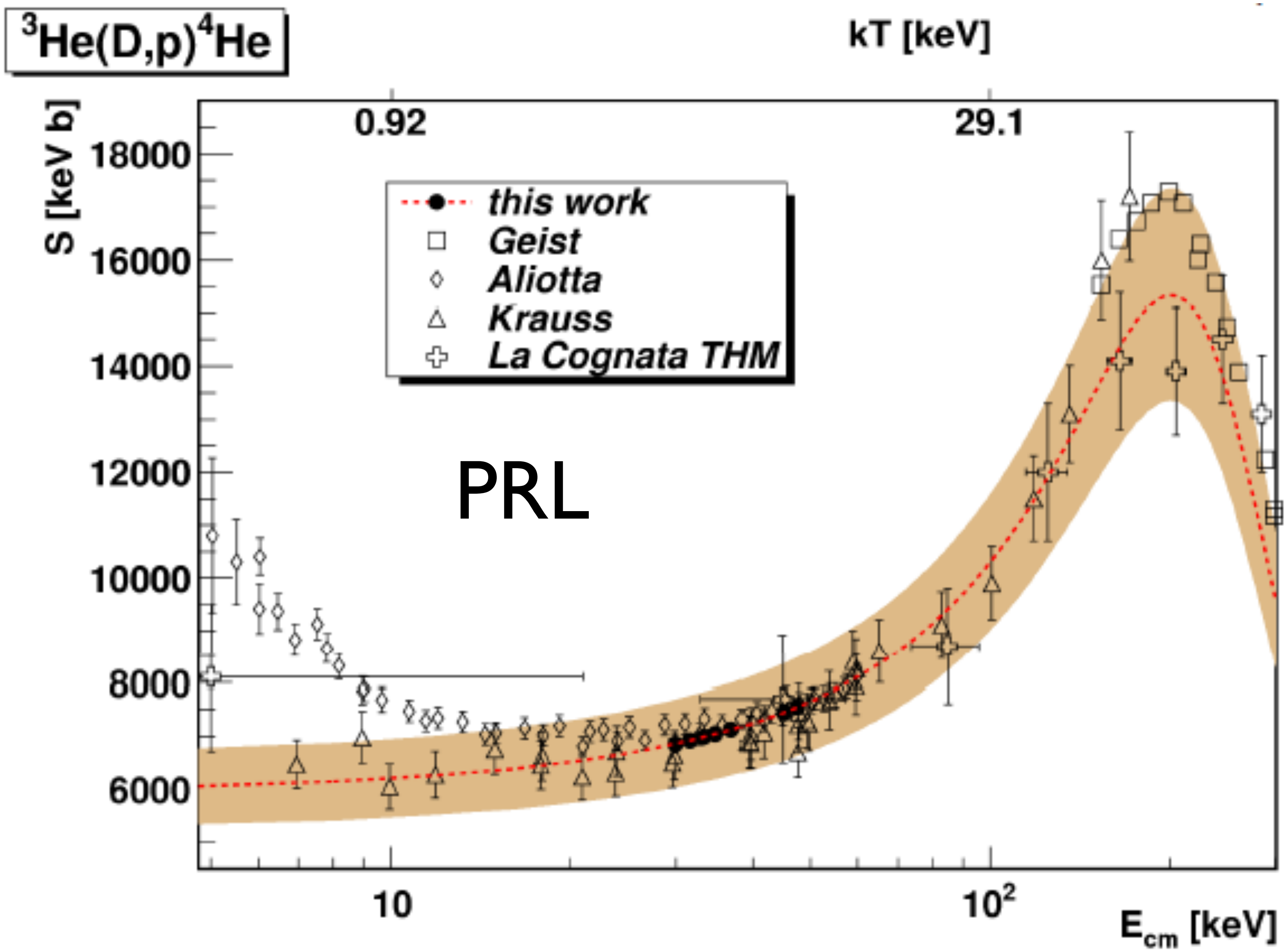
Yield of 14.7 MeV protons

Thin (254 um) plastic scintillators BC400.

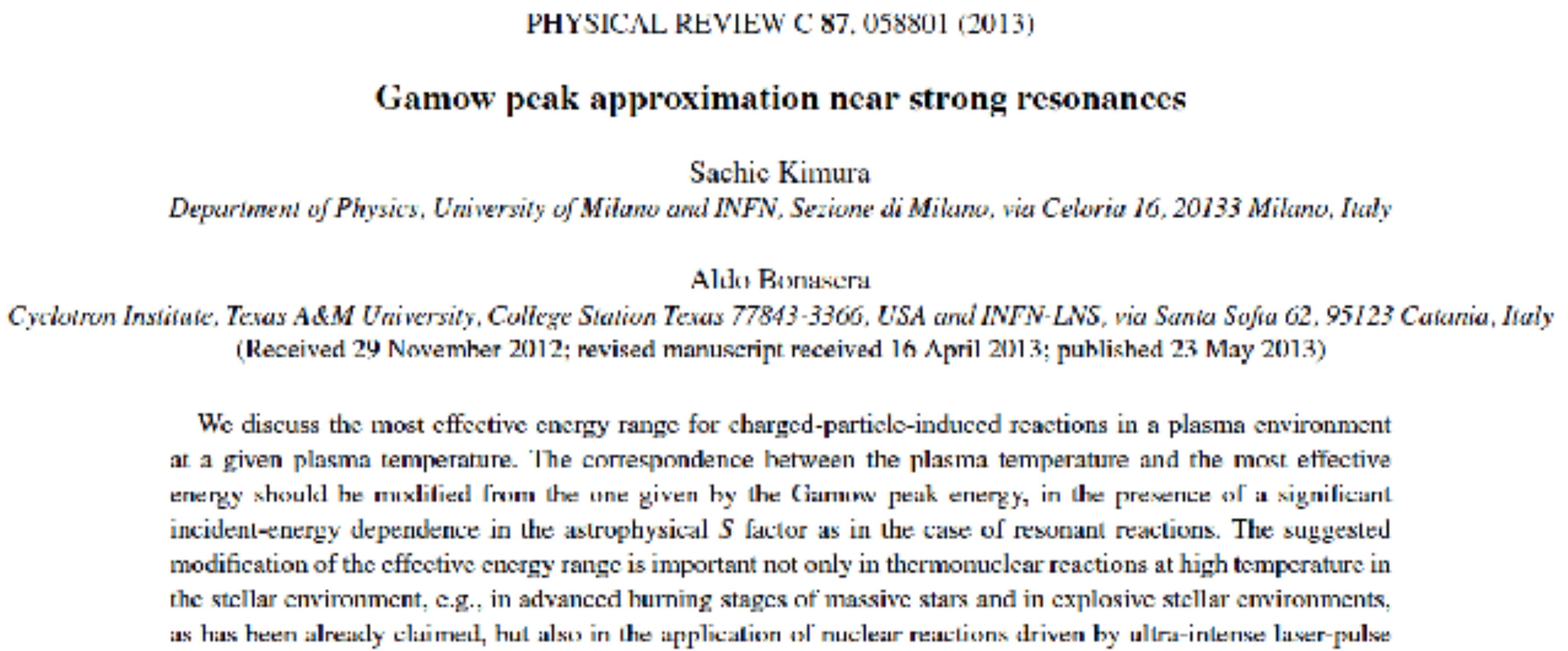




Measure N.of fusions for each channel



PRL



PHYSICAL REVIEW C 87, 058801 (2013)

Gamow peak approximation near strong resonances

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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

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R. De Angelis,[4] P. Andreoli,[4] E. Gaul,[1] A. C. Bernstein,[1] M. Donovan,[1] M. Barbarino,[2] S. Kimura,[3]
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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.

PHYSICAL REVIEW LETTERS

Measurement of the Plasma Astrophysical *S* Factor for the $^3\mathrm{He}(^2\mathrm{H}, p)^4\mathrm{He}$ 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]

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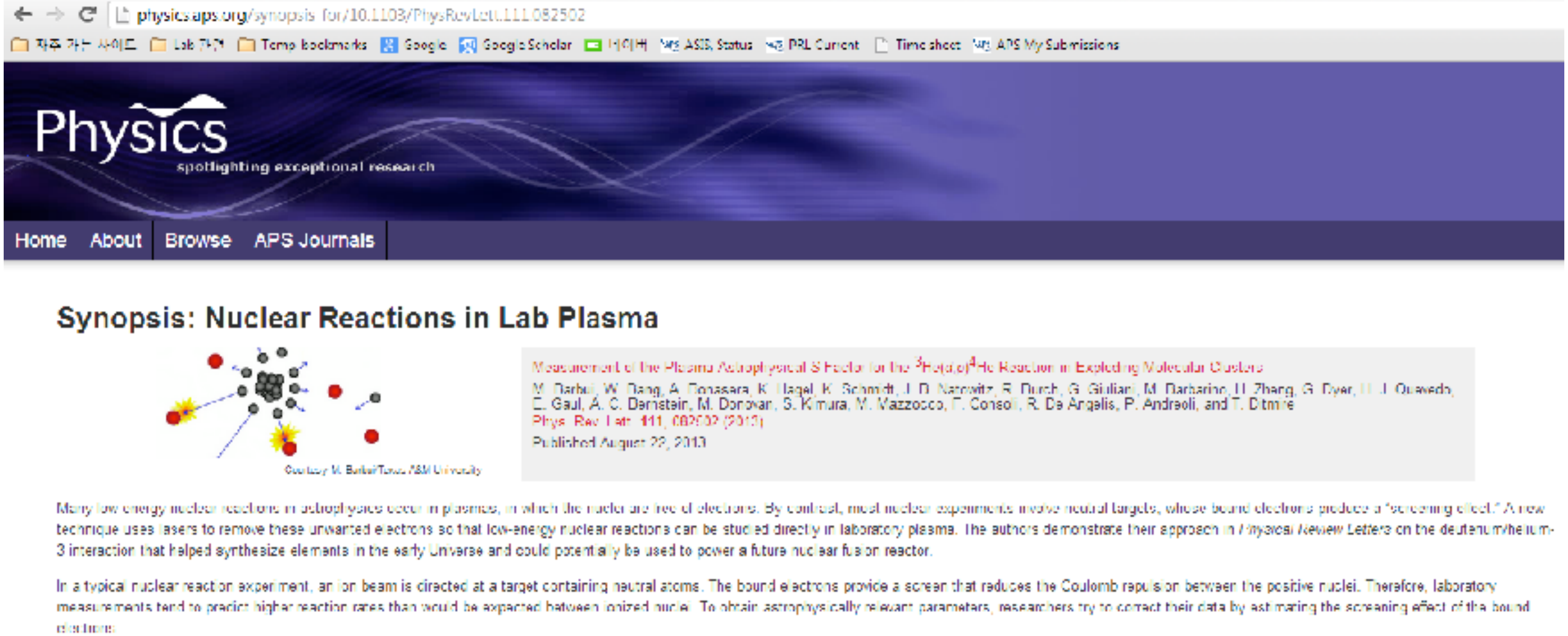
(Received 1 July 2013)



Synopsis: Nuclear Reactions in Lab Plasma

Courtesy M. Barbui/Texas A&M University

Measurement of the Plasma Astrophysical S Factor for the $^3\mathrm{He}(d,p)^4\mathrm{He}$ 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

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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]
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(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

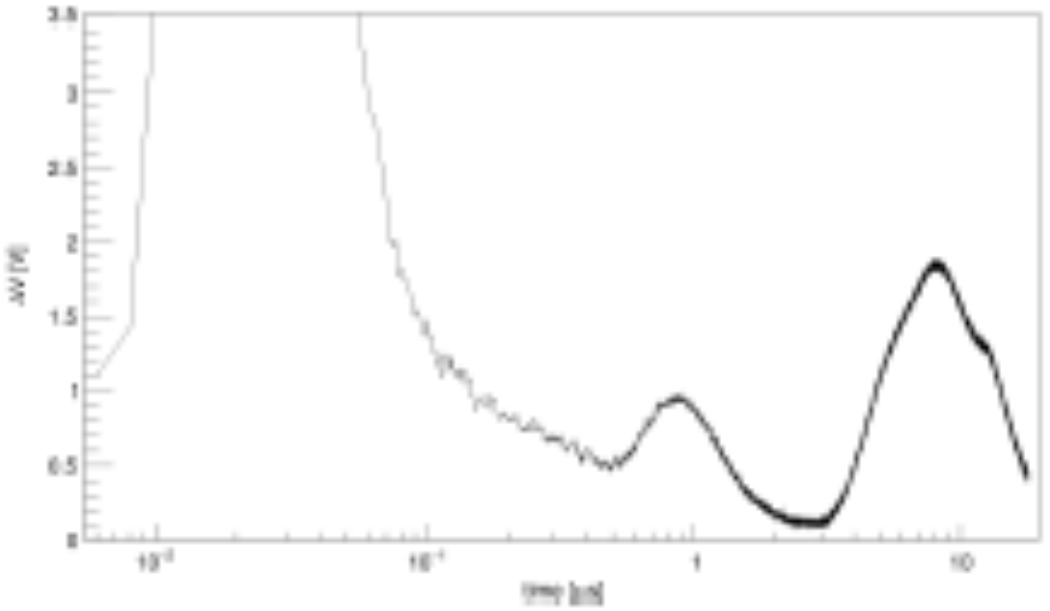


FIG. 1. The Faraday cup signal (ΔV) versus the time of flight of the deuterium ions recorded by the oscillope for one experiment of the campaign. The first steep peak whose tail extends to hundreds of ns overlapping with the second peak is due to the X-rays produced by the interaction of the laser inside the vacuum target chamber. The second small peak ($\lesssim 10^{-6}$s) is associated with energetic deuterium ions produced in the Coulomb explosion. The big wide double-featured peak at 3-20 μs is due to slower sub-keV ions resulting from the plasma wave propagation in the surrounding and cold cluster gas [16, 24]

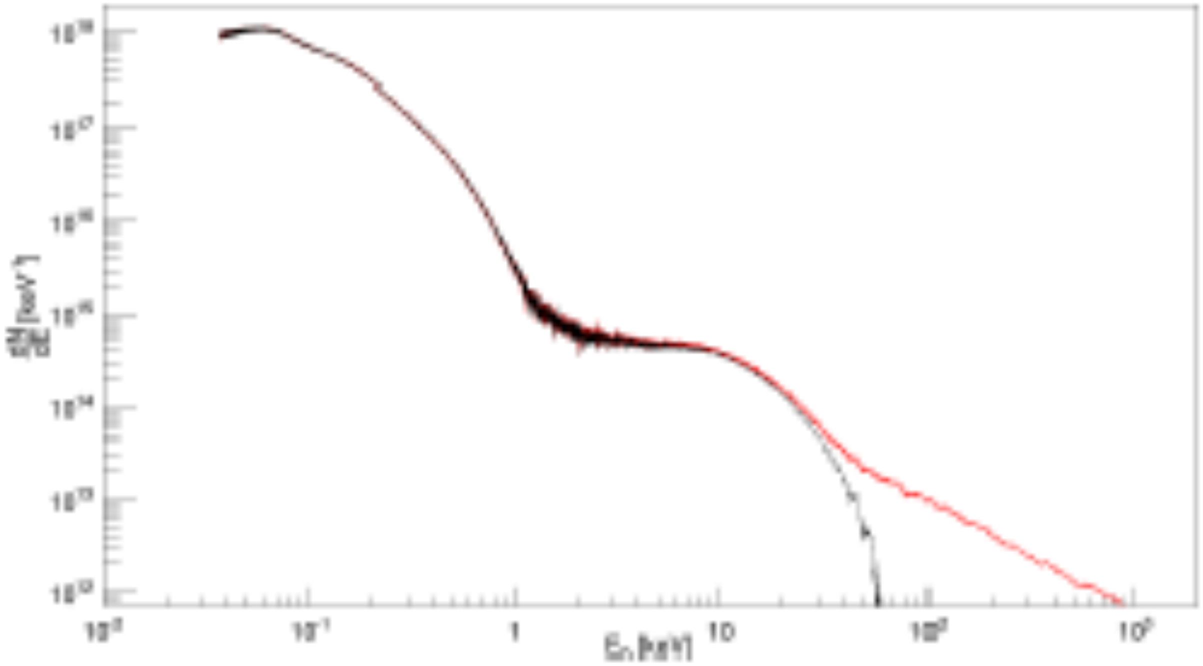


FIG. 2. Deuterium ion energy distribution as recorded in the FC (in red) and after background subtraction (black). The high energy tail is due to the x-ray noise from laser-cluster interaction.

recorded the arrival of energetic deuterium ions for 20 μs. The first spike whose tail extends up to hundreds of ns reached the full scale of the oscilloscope for all the shots of the campaign and it is due to the x-rays produced by the interaction of the laser and the target inside the vacuum target chamber. This feature is common in this

Make a good measurement of the ion distributions and get rid of the noise

IV. THE METHOD

For each shot, we can derive the S-factor at a given energy defined by the Gamow peak for the nuclear reaction (11) as

$$S_{d-d}(E_G) = \frac{1}{\int \Sigma_{d-d}(E)dE}. \tag{13}$$

where Σ_{d-d} is defined as:

$$\Sigma_{d-d}(E) = \frac{A_{BB} + A_{BT}}{Y_n^{(exp)}}, \tag{14}$$

where, using eq.(4),

$$A_{BB} = \rho_D l \int \frac{dN}{dE} \frac{\exp(-2\pi\eta E)}{E} dE \Big|_{dd[BB]} \tag{15}$$

and

$$A_{BT} = \rho_D (R - l) \int \frac{dN}{dE} \frac{\exp(-2\pi\eta E)}{E} dE \Big|_{dd[BT]}. \tag{16}$$

Similarly

$$S_{d^3He}(E_G) = \frac{1}{\int \Sigma_{d^3He}(E)dE}. \tag{17}$$

where

$$\Sigma_{d^3He}(E) = \frac{B}{Y_p^{(exp)}}, \tag{18}$$

and

$$B = R\rho_{^3He} \int \frac{dN}{dE} \frac{\exp(-2\pi\eta E)}{E} dE \Big|_{d^3He}. \tag{19}$$

For each event, we assume that the S-factor is nearly constant and the Gamow peak energy is a good representation of the energy at which nuclear reactions mostly occur. Since we have measured the number of fusions and the distribution function, we can easily evaluate the integrand in equations (13) and (17) by using the experimental ion distribution function, after background subtraction, in order to provide an evaluation of the S-factor. This is the essence of the proposed method and it is clear that the major sources of uncertainties are the

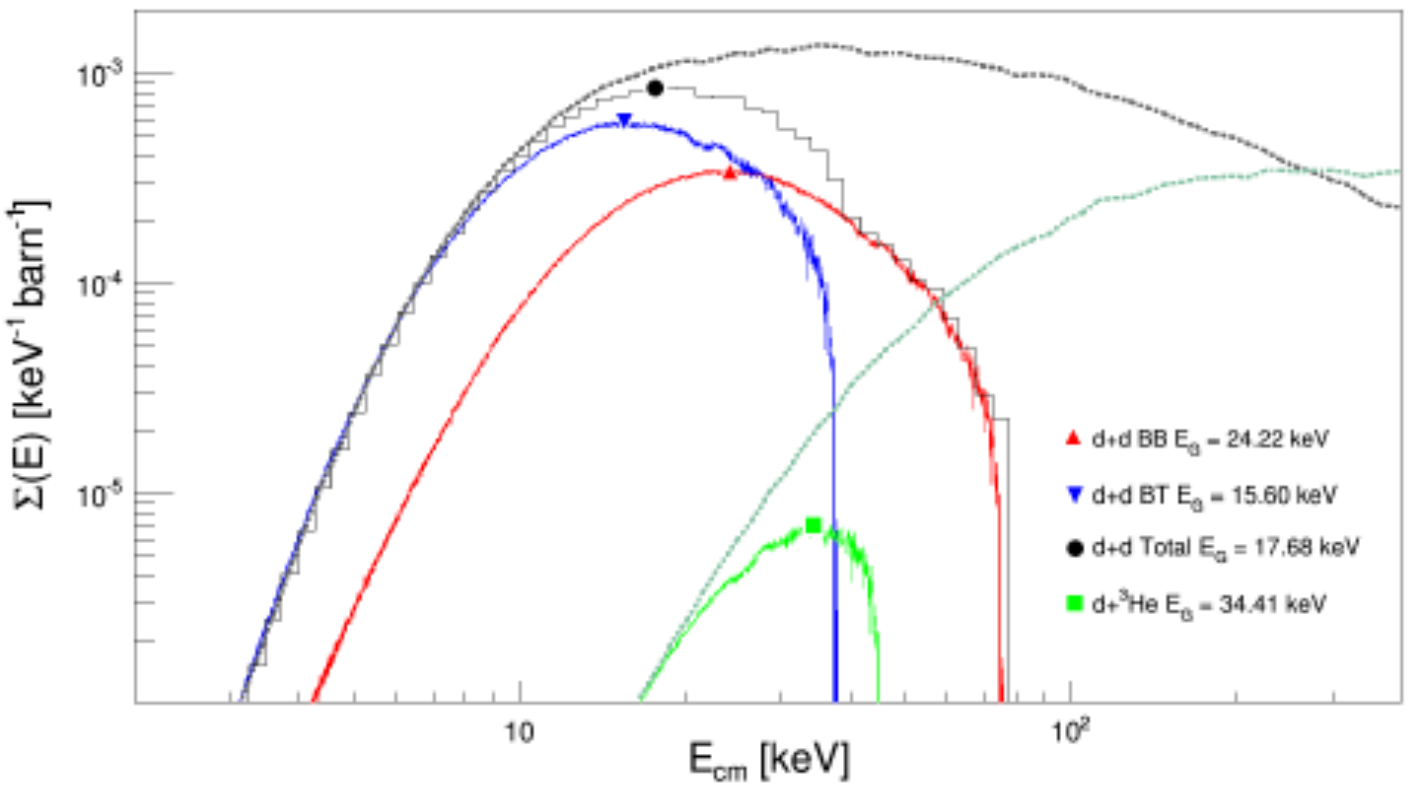
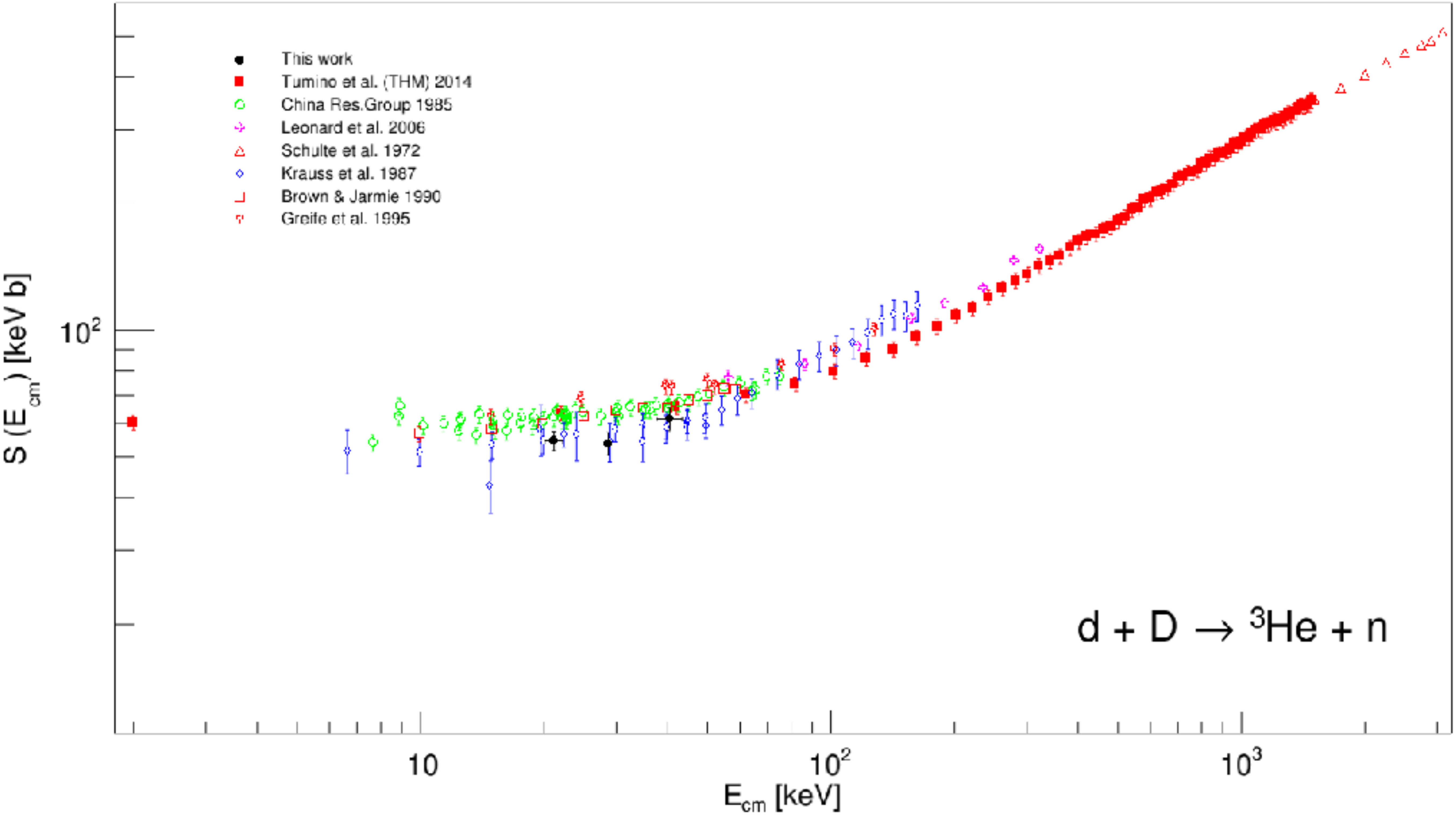
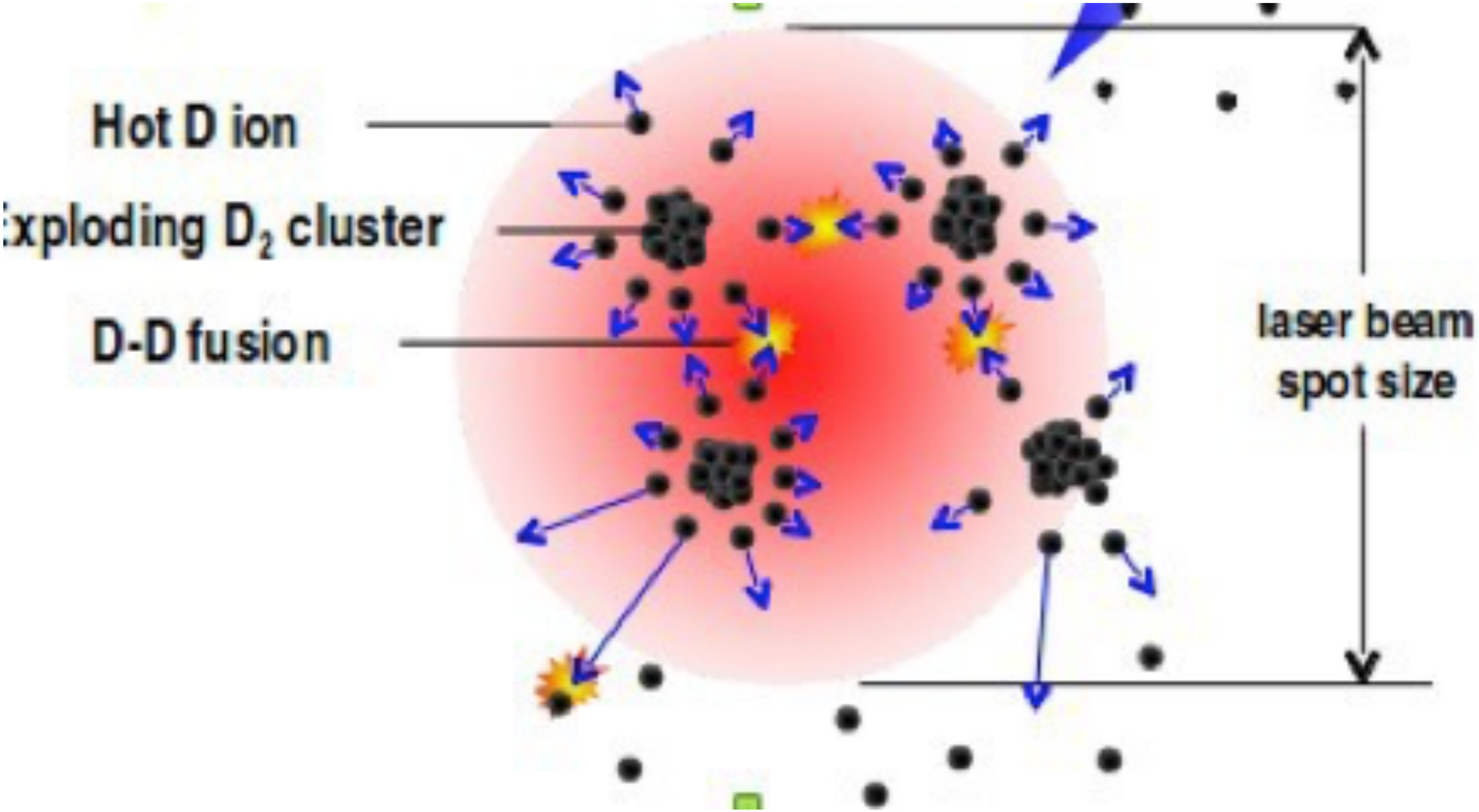


FIG. 4. Σ(E) for the nuclear reactions (1) and (3) is plotted versus the center-of-mass energy of the fusion nuclei. The area under the curves gives the inverse of the S-factor. The d+d *BB* (in red) and *BT* (in blue) contributions are plotted together with their sum (binned, black) and the d+^{3}He one (green). The latter are also plotted without applying any background cut (thick dashed grey and cyan lines). The maximum of this quantity locates the Gamow peak energy. The solid (red) up and (blue) down triangles respectively represent the BB and BT contributions of (1), the solid (black) circle is their sum and the solid (green) square is used for the reaction (3).


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 → ^{3}He + n



Plasma is a harsh environment. If the collisions occur in the presence of electrons, the probability might go up

If they occur in the presence of positive charges, probability might go down: DISSIPATIVE LIMIT

[11] S. Kimura, A. Bonasera, Influence of the electronic chaotic motion on the fusion dynamics at astrophysical energies. Nucl. Phys. A **759** (2005) 229244.

Physics Letters A 381 (2017) 1682–1686

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

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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

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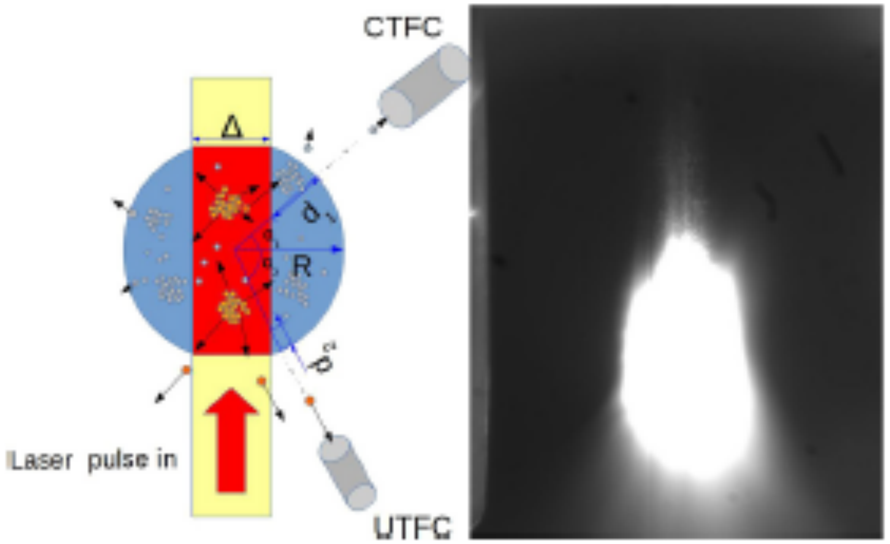

Fig. 1. a) Schematic view of the experimental setup with the location of the two Faraday cups respect to the impinging laser beam; b) image obtained in one shot (#9700) using a D_2 gas. Δ is the laser focalization and *R* the nozzle opening. The nozzle is visible on the left hand side of Fig. 1b.

expansion from the critical point might be very different respect to the log-normal distribution [16,17].

The laser ionizes the clusters and the ions expand quickly because of the Coulomb repulsion. Those energetic ions might move in all directions including the cold region as schematically shown in Fig. 1a, and can be absorbed by a cluster on its path of size R_c with a probability essentially given by the geometrical cross section. Notice that if no cold region is present, which can be obtained by opportunely defocussing the laser beam or decreasing (increasing) the nozzle pressure (temperature), the final ion angular distribution becomes isotropic. If the plasma ion is very energetic it can break clusters of relatively small sizes thus producing low energy ions. This 'multiplication' effect has been discussed already in the literature as a 'blast wave' [1–14]. Depending on the cluster size distribution we can have different ion ranges somehow dependent on the initial pressure and temperature of the gas inside the valve [20]. In this scenario we can study the influence of the initial conditions on the ion range and in particular see the effect of the system prepared in a particular state, near the LG phase transition as we will discuss below. There is no need to stress the importance of exactly measuring the range of keV ions in particular states of matter to understand the influence of the phase transition on nuclear fusion reactions. We also measured the fusion yields in the very same conditions and its analysis is in progress.

In our experiment, the Texas Petawatt laser (TPW) delivered 50–100 J per pulse with duration 150 fs–2 ps [21] to irradiate the clusters. It utilized an f/40 focusing mirror (10 m focal length) to create a large interaction volume with laser intensities sufficient to drive fusion reactions. This laser power and focusing geometry increased the neutron yield many times that of previous cluster fusion experiments [10]. Recent improvements in the laser architecture resulted in pre-pulses in the TPW system with intensities

In Fig. 2, we plot the ion distributions for different shots using D_2, CD_4 and N_2 gases, respectively. We have tested that the two FC measure the same ion current when Δ in Fig. 1 is of the order of the nozzle diameter (5 mm). When the plasma ions travel through cold regions of size d_1, d_2 in Fig. 1a, they might be scattered, absorbed or slowed down. The ion distribution measured by the FC (UTFC), which sees the hot plasma, is degraded and measured by the second FC (CTFC):

$$\frac{d^2N}{dEd\Omega}(CTFC) = \frac{d^2N}{dEd\Omega}(UTFC)e^{-\frac{\delta}{\lambda}} \tag{1}$$

where λ is the ion range in the cold cluster gas, $\delta = d_1 - d_2$. We notice that for most of our shots d_2 is equal to zero.

The ion distributions and the range obtained from equation (1) are plotted in Fig. 2 as function of the energy per particle. The SRIM results for a homogeneous gas at different densities are given in the bottom panels with full and dashed lines. This work (see below) and previous experimental results give densities of the order of 10^{18} atoms/cm^3 [1–10]. Also, SRIM range results for C ions propagating in the cold gas are given for the CD_4 case, center bottom panel of Fig. 2. Notice that when plotting the SRIM results as a function of the energy per nucleon (2, 12 and 14 for d, ^{12}C and ^{14}N respectively), completely different stripped ions (i.e. C and D) scale quite well at the given density (Fig. 2 bottom-center panel). This implies that the slowing down of ions in homogeneous matter is essentially dependent on its velocity and not on the energy. Another feature to notice is that the SRIM results depend linearly with the density, Fig. 2, thus the quantity $\lambda\rho$ is expected to be independent of density, see below [15]. The SRIM calculations are in complete disagreement with our results since the experimental in-homogeneous cluster gas distribution is in contrast with the theoretical uniform distribution. The EMP affects the high-energy tail of the ion distribution. Since the FCs are located at different distances the EMP dominates earlier the signal of the FC located closer. This is especially visible in the center and right panels of Fig. 2 since the CTFC was located at 3 m while the UTFC was at 1.1 m from the target. The change of slope in the UTFC ion distribution below 100 keV/nucleon reflects a sudden increase in the range. We can assume that the range is fairly constant at least in the region 1–80 keV and maybe even for higher energies. Depending on the gas density, the experimental range differs from the SRIM calculations by orders of magnitude. Notice that different clusters, either D, a mixture of C and D or pure N gases give similar ranges and any deviations are due to the initial pressure and temperature at the nozzle. This is consistent with the Coulomb explosion model since all ions have the same charge over mass ratio, thus we expect that a mixture of ions (for instance in CD_4) have the same energy per nucleon distribution and similar range.

We can estimate the range of plasma ions in a cluster gas at average particle density ρ. The gas is composed of different clusters of size R_c. The mean free path of an ion in the cluster gas can be estimated classically as:

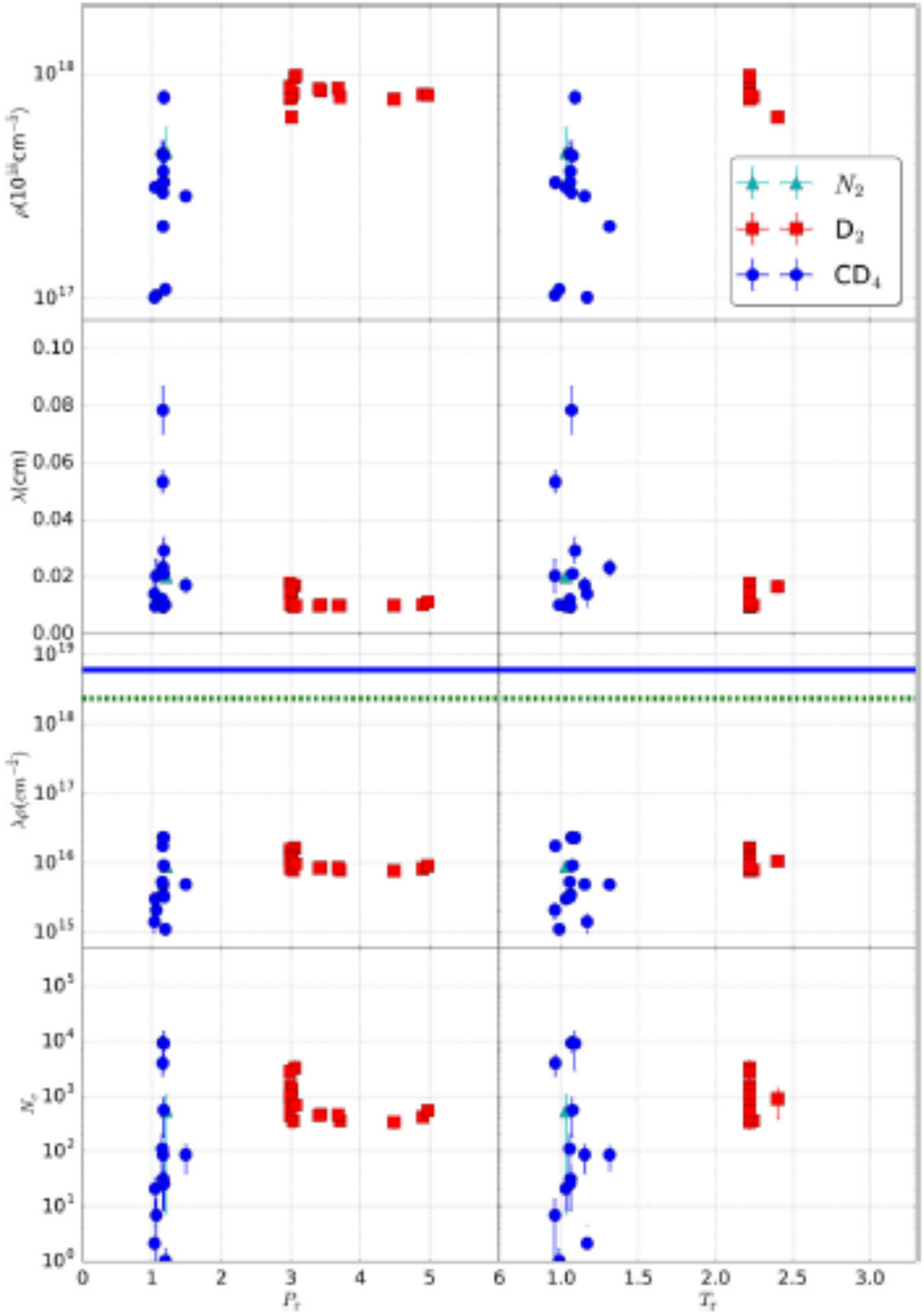

Fig. 3. From top to bottom: density, range, density times range and average number of cluster obtained from eq. (5) vs reduced pressure (left panels) and reduced temperature (right panels). The full (D_2) and dashed lines (CD_4) in the third panel are the SRIM results (independent on density) averaged over the same energy range.

Neutron enhancement from laser interaction with a critical fluid

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3) Laboratori Nazionali del Sud-INFN, via S. Sofia 64, 95123 Catania, Italy.
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Abstract

We discuss neutron production from a system prepared near the liquid-gas critical point. The petawatt laser at the University of Texas-Austin was focused on a cluster gas producing a hot plasma. Using deuterated methane, it is possible to prepare the system very close to its critical temperature and pressure. We let the fluid expand through a conical nozzle and irradiate it with the laser. After the ionization, the clusters explode and the collision of two energetic ions might produce neutrons from fusion reactions. 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 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 deuterated methane (CD_4) cluster

October 13, 2014

Dr. Aldo Bonasera
Texas A&M university
Cyclotron Institute
college station, TX 77843
abonasera@comp.tamu.edu

Dear Dr. Bonasera:

Thank you for submitting your proposal for NIF Discovery Science (DS) entitled: *"Dynamics of fusion in hot and dense plasmas: influence of the electronic motion and non-equilibrium effects on the astrophysical S-factor"*

Proposal Category: Platform Development

As part of our process for evaluating the NIF DS proposals, we would like to invite you to defend your proposal during the peer review process via **web conference**. Detailed web conference instructions will be emailed one week prior to your presentation**:**

Date: Wednesday, November 12, 2014
Time: 8:55 - 9:20 AM (PST)

The defense presentations will be allocated 25 min. total: 15 min. for the presentation and 10 min. for discussion. Please follow the guidelines below, using the suggested number of viewgraphs (vgs) in each section as an upper bound, and prepare no more than 10 vgs total for your presentation:

- **Development objectives:** the science that would be enabled by this new capability; expected impact to the field; the need for this capability to be developed on NIF (as opposed to other facilities); quantitative description of the goals of the development project; and an estimate of what fraction of the proposed capability development can be accomplished in the 18 months under consideration for your proposal. (1-2 vgs)
- **Development approach:** the development method and how it will be tested, such as modifying or enhancing a diagnostic, developing a new diagnostic, developing a new target or capsule type, developing a new laser configuration, developing a new experimental configuration, and/or carrying out experiments and development work at other relevant facilities. (2-3 vgs)
- **Laser requirements:** if shots are required for this capability development proposal, describe the number of laser beams, laser energy/beam, peak power/beam, pulse shape, pointing, delay, backlighter beams (energy, power, pulse shape, pointing, delay), phase plates, other non-routine requirements. (1 vg)

Dynamics of fusion in hot and dense plasmas: influence of the electronic motion and non-equilibrium effects on the astrophysical S-factor.

PI: A. Bonasera[a,b]

a) Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA, (+1)9798451411, abonasera@comp.tamu.edu;
b) Laboratori Nazionali del Sud, INFN, via Santa Sofia, 62, 95123 Catania, Italy, (+39)095542289, bonasera@lns.infn.it.

Synopsis: Nuclear Reactions in Lab Plasma

Measurement of the Plasma Astrophysical S Factor for the ^{3}He(d,p)^{4}He 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)

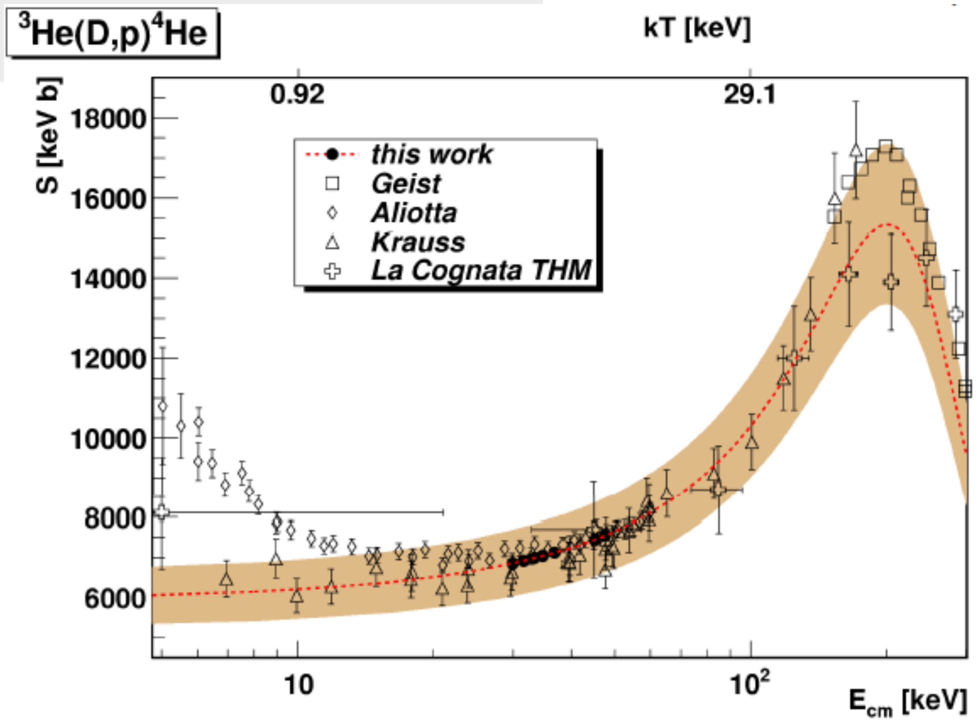
Published August 22, 2013

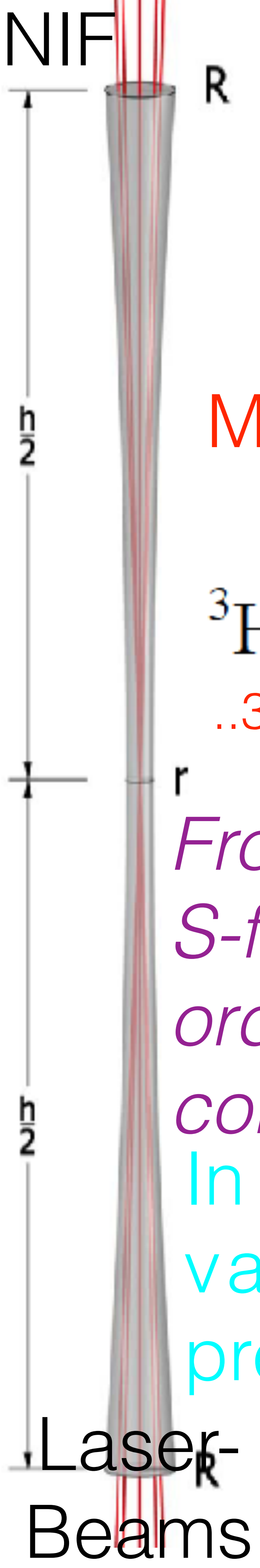
Courtesy M. Barbui/Texas A&M University

PRL 93, 262502 (2004) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2004

Chaos Driven Fusion Enhancement Factor at Astrophysical Energies

Sachie Kimura and Aldo Bonasera





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—>a+n

d+d—>^{3}He+n(t+p)

t+t—>a+2n

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

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

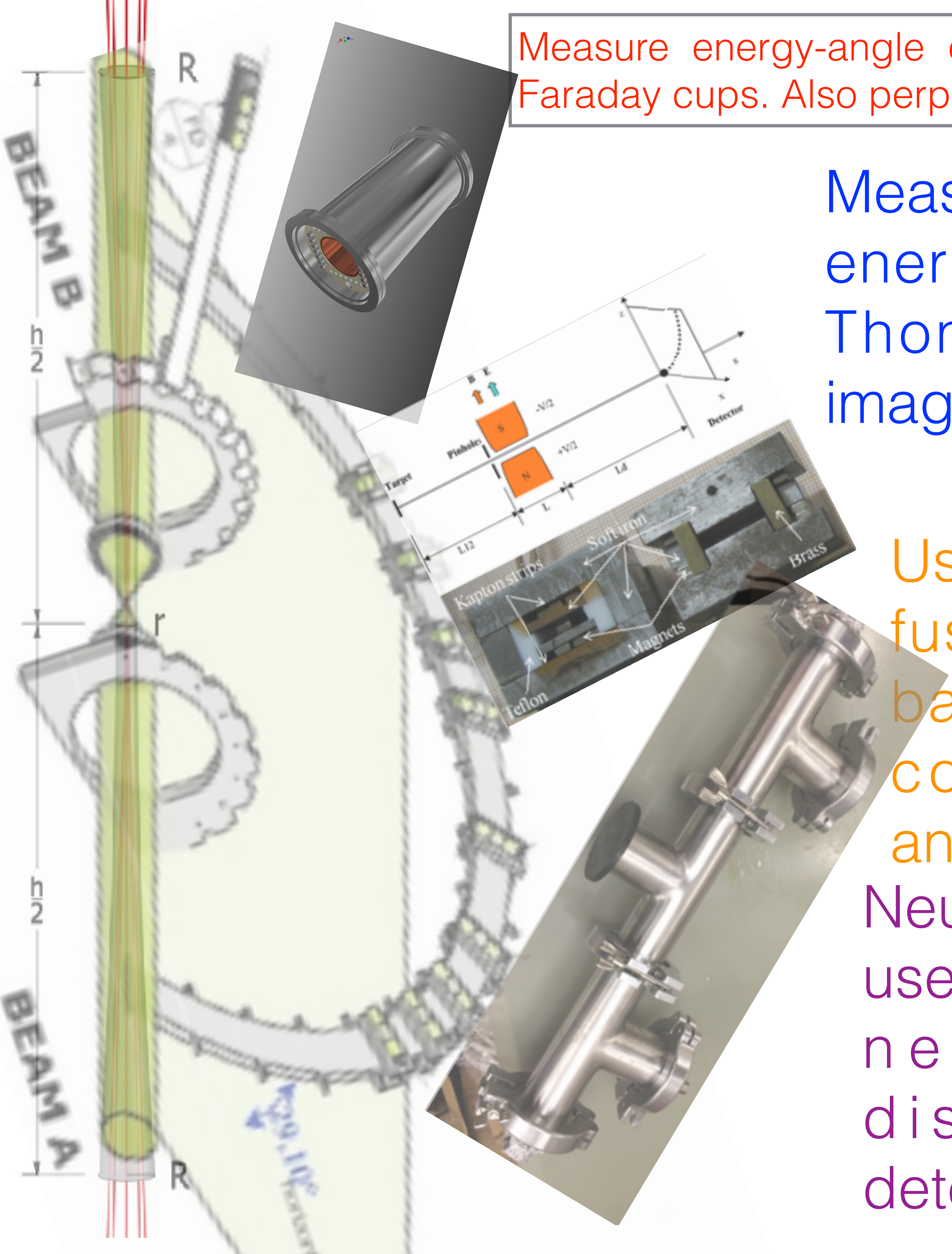
$^3He+\alpha \rightarrow {}^7Be+\gamma$ $\quad {}^7Li+t \rightarrow {}^9Be+n$ $\quad {}^9Be+\alpha \rightarrow {}^{12}C+n$ $\quad n+{}^7Be \rightarrow 2\alpha$

..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.

Measure energy-angle distributions of the plasma ions using Faraday cups. Also perpendicular to the laser beams.

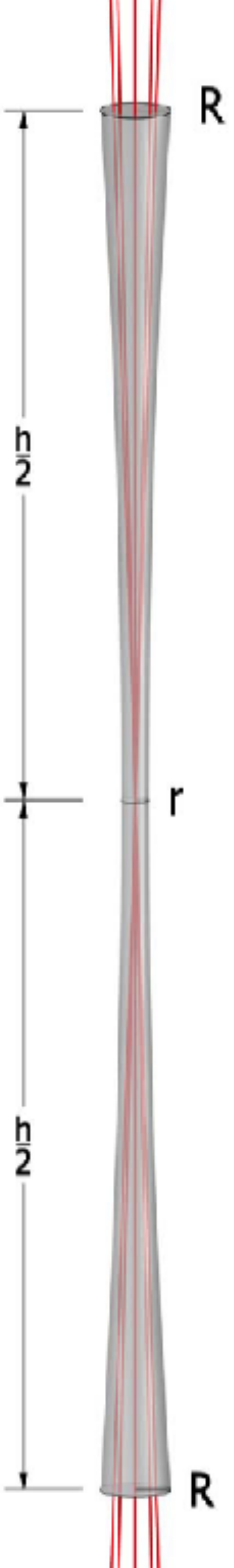


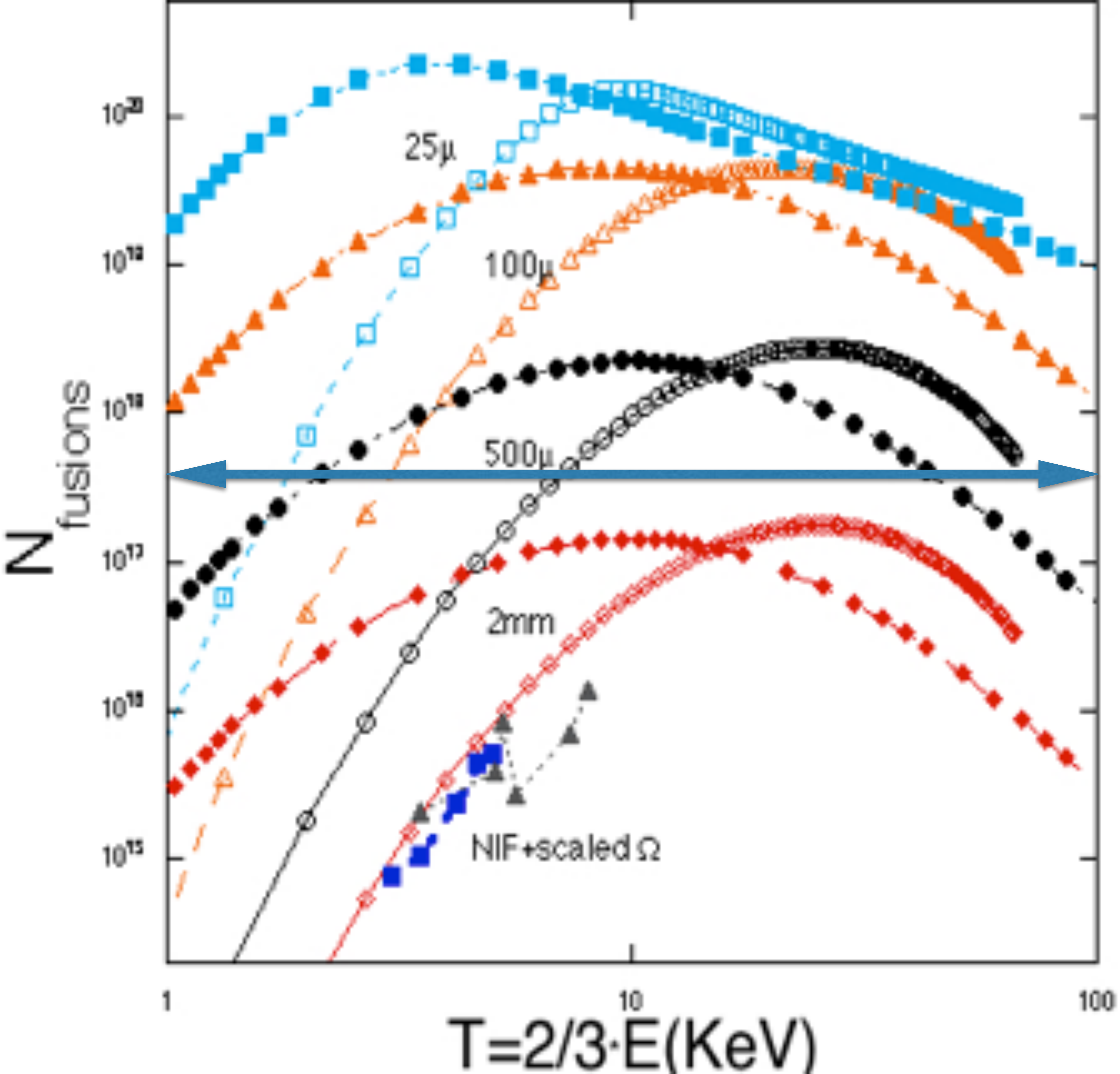
Measure ions having kinetic energies >100KeV using Thomson parabola and image plates or similar.

SCHEMATIC

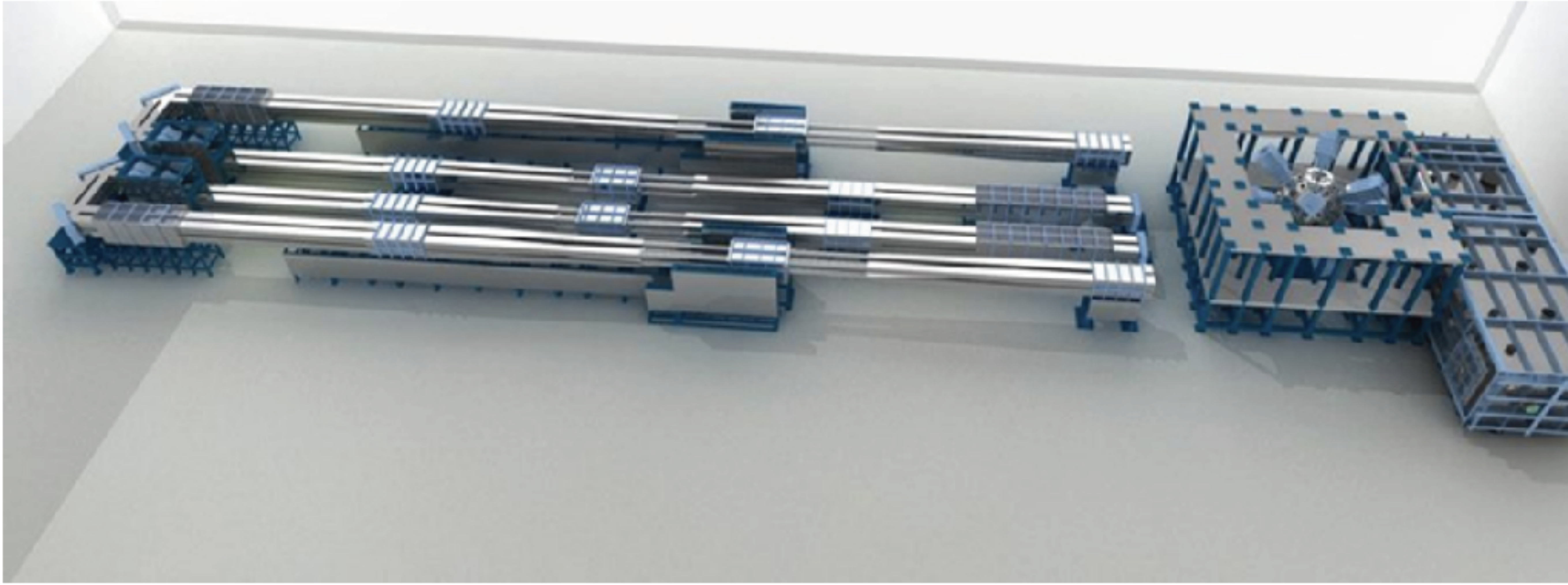
Use scintillators for charged fusion products+CR39 as backup detectors+foils to collect debris for later analysis.

Neutron detectors already in use @NIF +more detectors if needed for angular distribution+diamond detectors


R
h/2
r
h/2
R


$N_{fusions}$
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
25μ
100μ
500μ
2mm
NIF+scaled Ω
1
10
100
T=2/3·E(KeV)

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

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 → ^{3}He (0.82 MeV) + n (2.45 MeV)

d + d → t (1.01MeV) + p (3.02 MeV)

d + t → ^{4}He (3.5MeV) + n (14.1 MeV)

d + ^{3}He → ^{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)

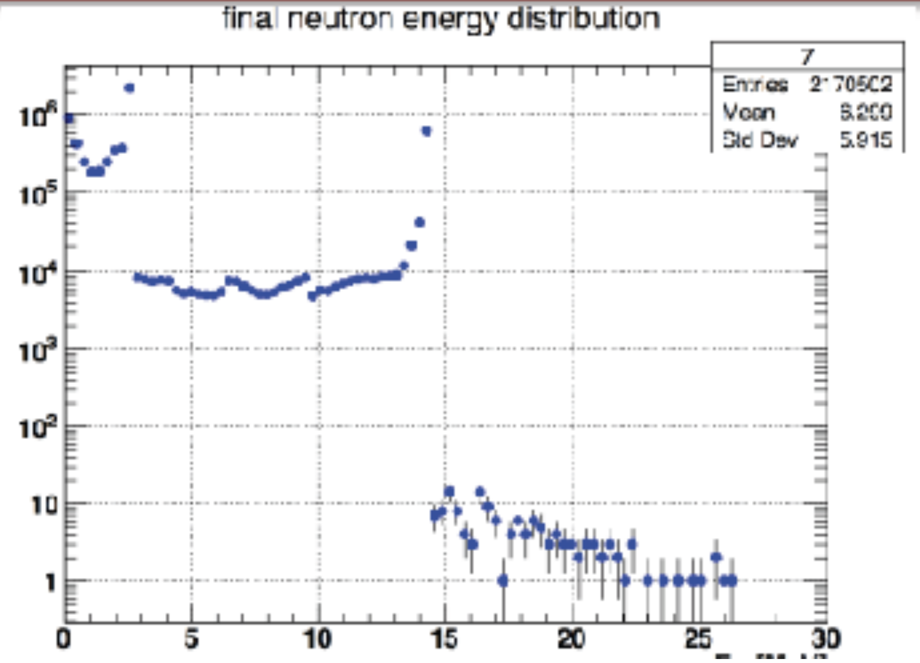
Nf1 **Nf2** **n(2.45 14.1MeV)** **NDs** 10^6

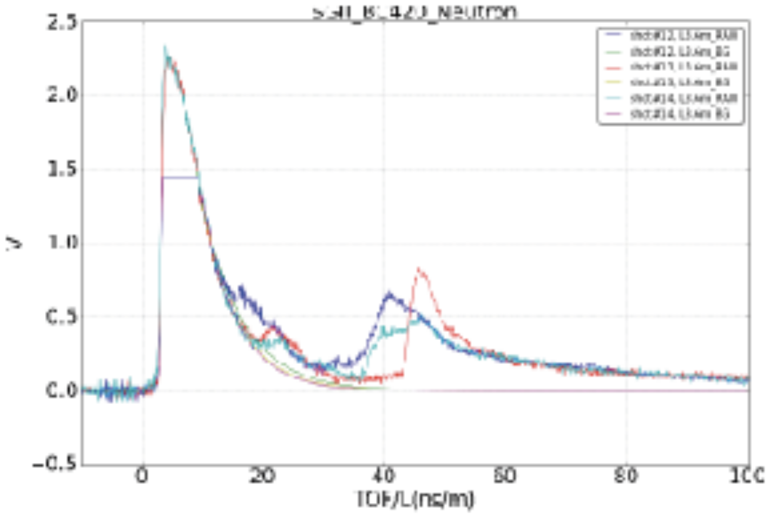
1:5

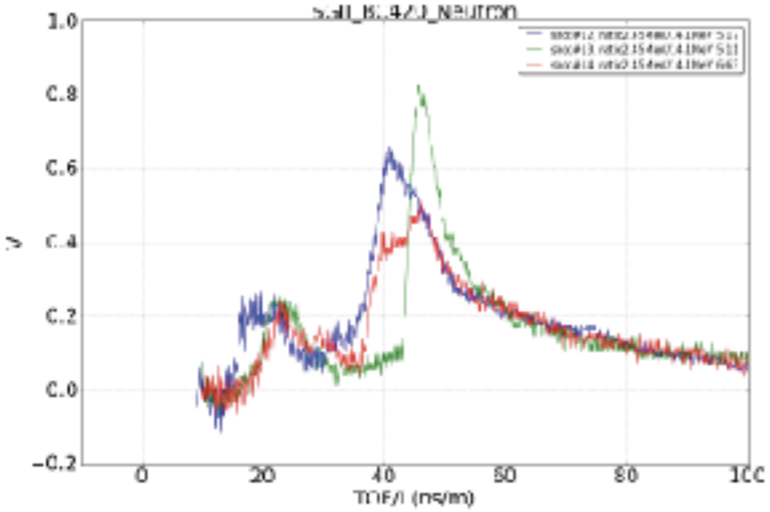
what is the number of 2.45MeV neutron should we have?

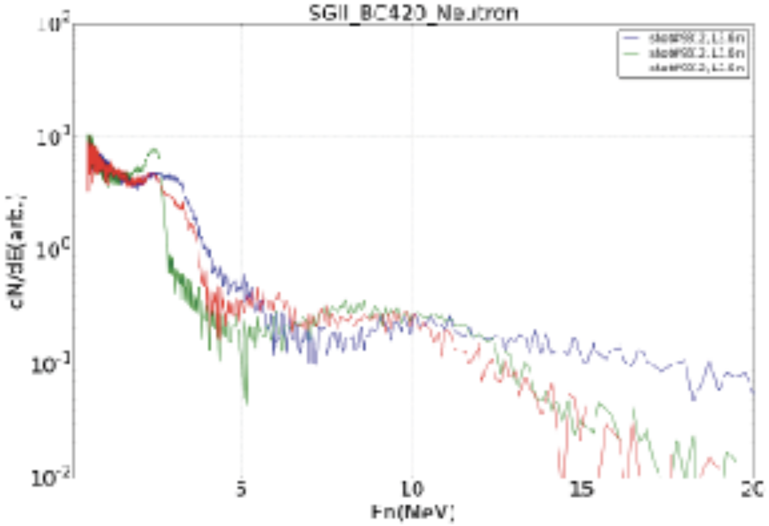
Neutrons would scatter between the walls.
longer TOF
Neutrons would scatter with D and C and deplete the neutron peaks

What is efficiency of our NDs?
What is one neutron signal? the height \the area\ the HV
How many plastic bricks and lead bricks do we need to stop the EMP or x ray?
Geant4 simulation





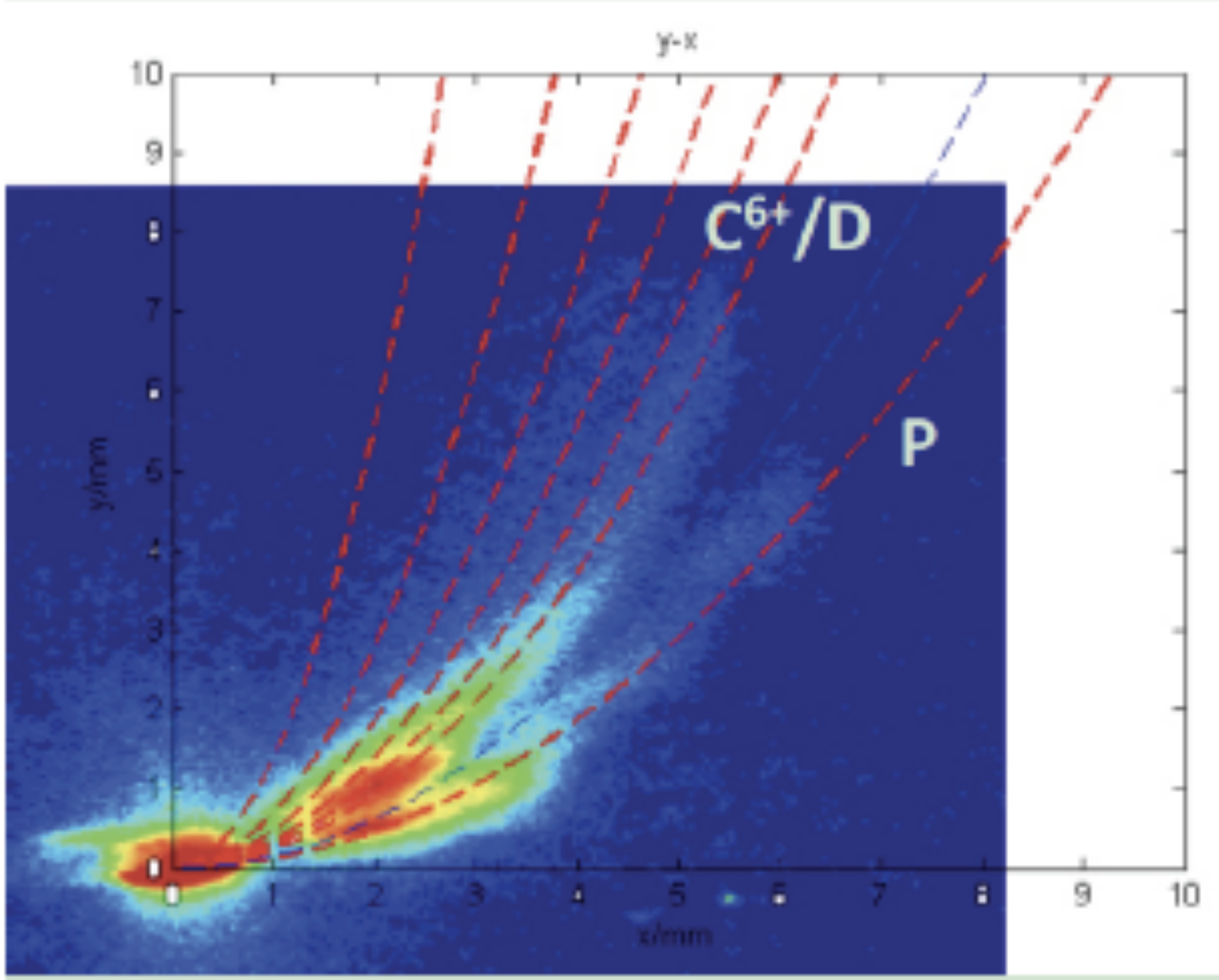


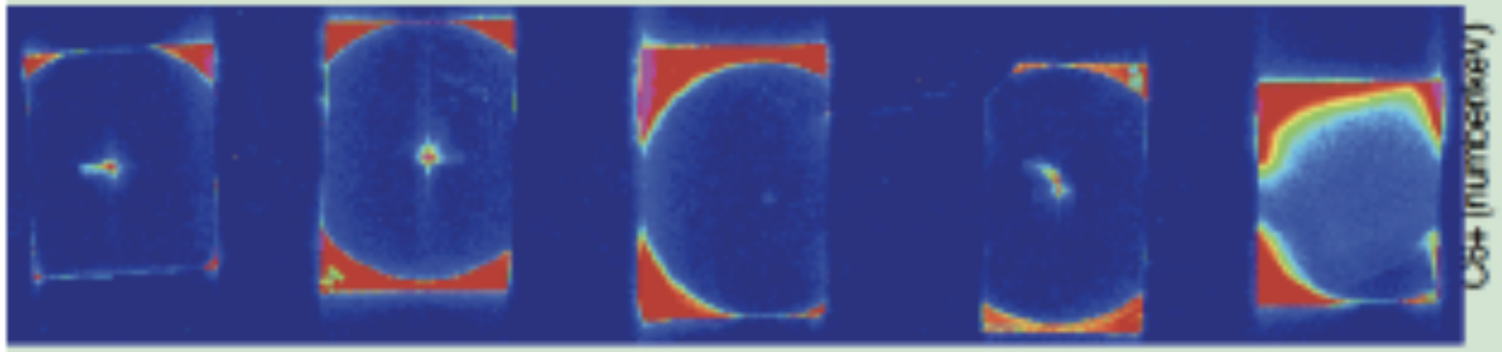


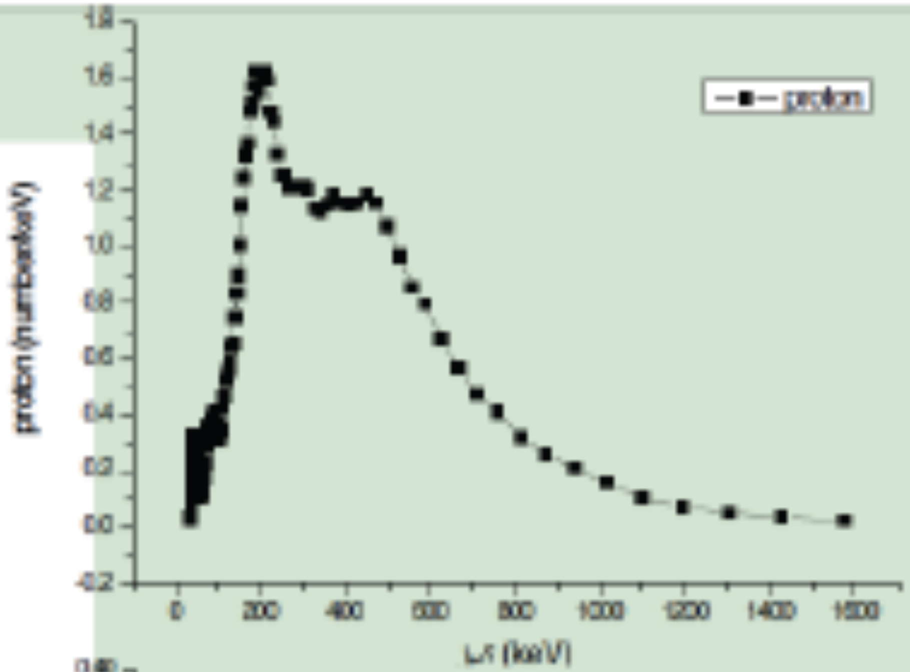
zhangguoqiang2017-04-13 @SINAP

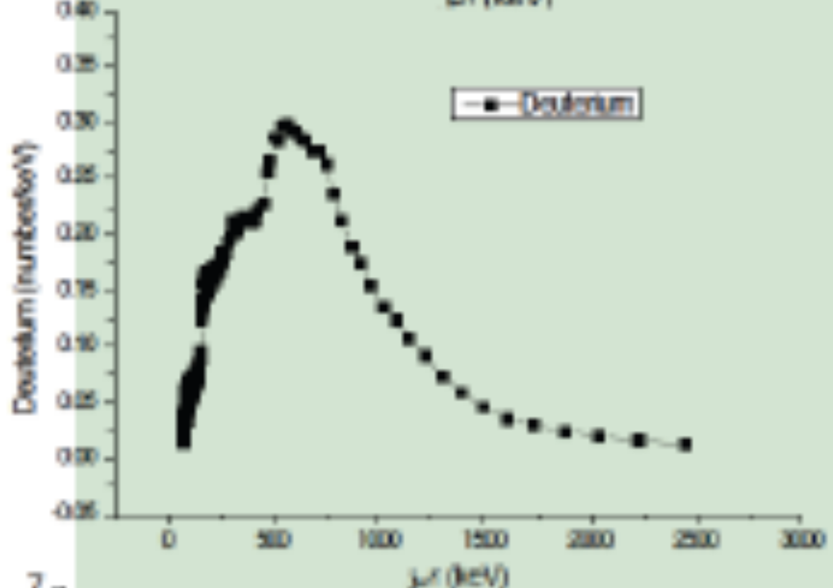
Shot 10

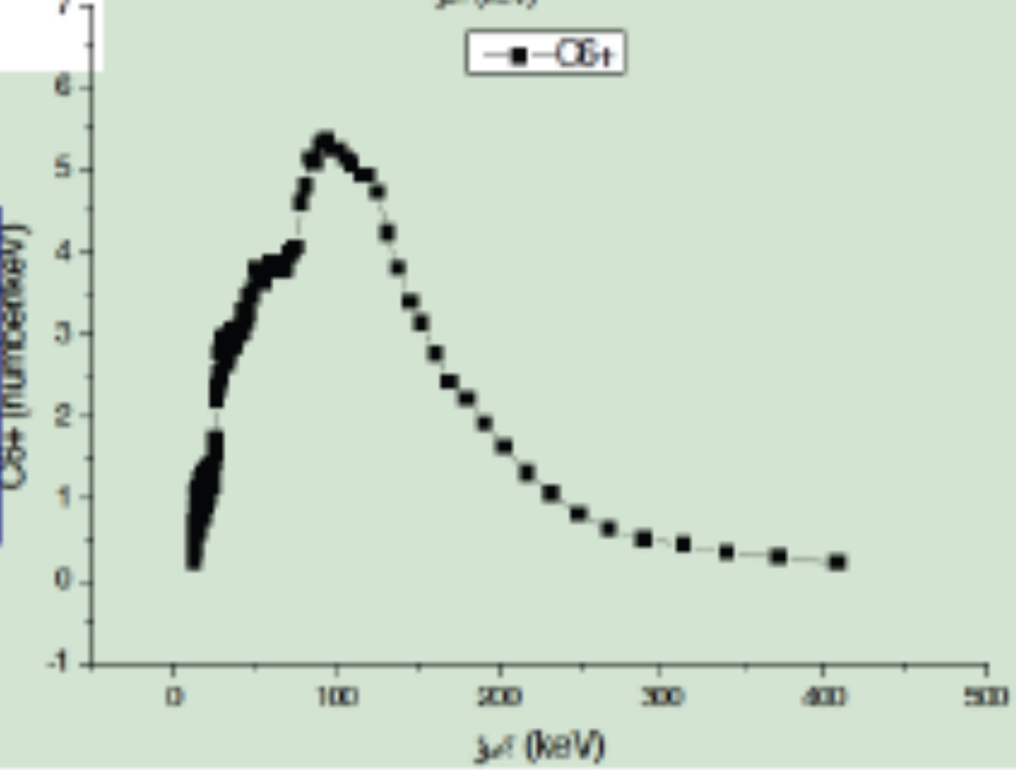
No.4 TP











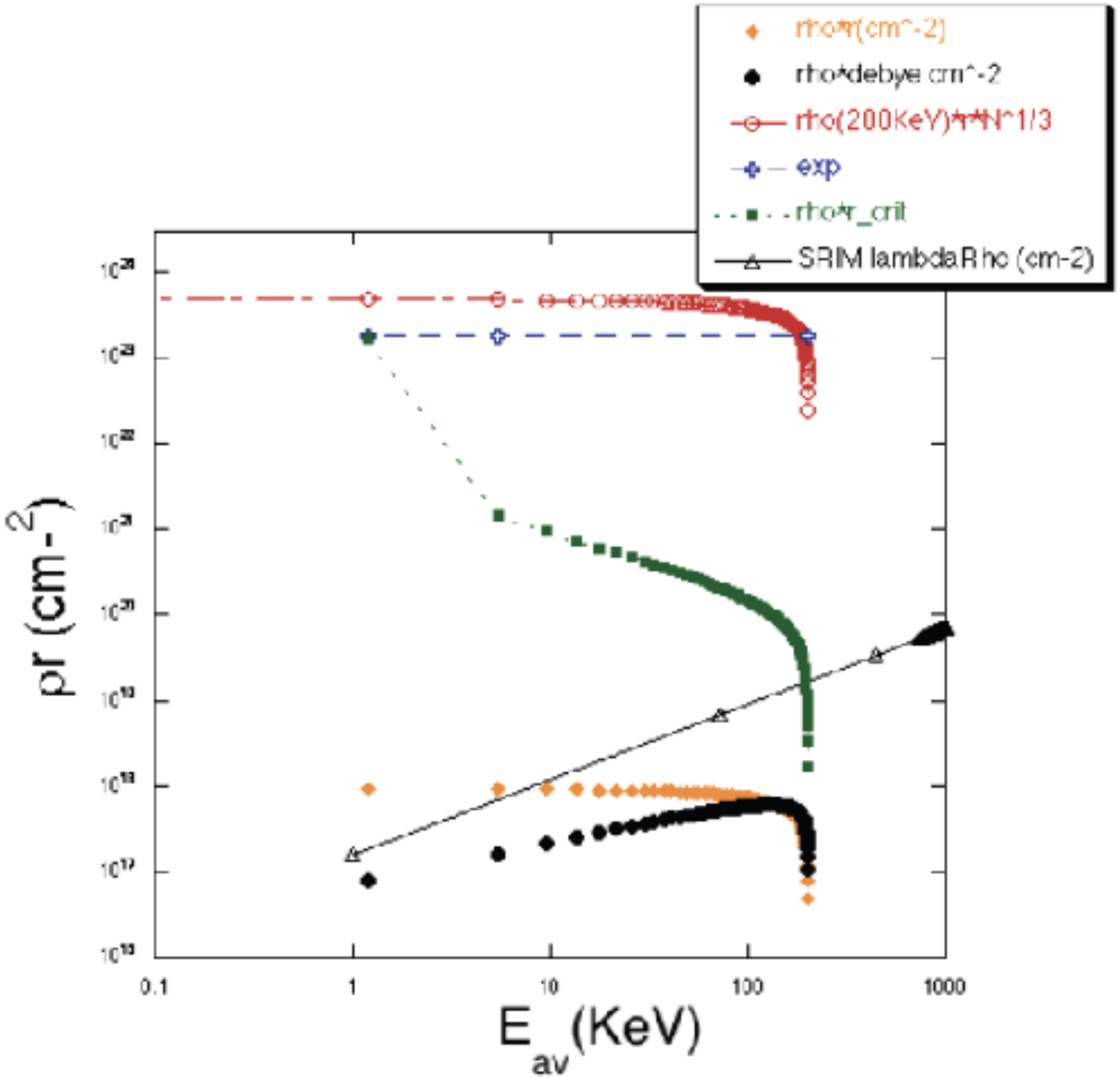
ρr Nf2/Nf1/<σ>

10^26 cm-3

EOS of the plasmas? phases?

high energy particles?

interferometer for density in the future?



$$\frac{E}{N} = E_{av} + \frac{A}{2}\bar{\rho} + \frac{B\sigma}{\sigma+1}\bar{\rho}^{\sigma}$$

$$r_{crit} = r_0 \left|\frac{T - T_c}{T_c}\right|^{-\nu}$$

CONCLUSIONS

- Next stops:
- d+t
- d+d+232Th+…

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 Bang 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 Barbarino Sachie Kimura [b], Jozef Sura [f], Joseph Natowitz [c], Todd Ditmire [e]

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Thank you !