Million degrees Celsius for igniting fusion is not longer needed: use non-thermal ps-CPA-laser pulses

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REACTION ENERGY

NUCLEAR HUNDRED MILLION TIMES HIGHER THAN CHEMICAL: CARBON

IGNITION TEMPEARATURE NEEDS DOZENS OF HUNDRED MILLION DEGREES FOR NUCELAR FUSION

HIGH THERMAL PRESSURES SUBSTITUTED BY NON-THERMAL LASER PRESSURES

Energy source

<u>Wealth of civilization</u>:by Newton's Physics & James Watt's steam engine

<u>Burning carbon</u>: until 1950 acceptable

2020 five times too high

2050 ten times too high

<u>Climate Change</u>: 10 years child' mathematics: melting Greenland ice results in 7 meter higher ocean level

European President (Council) Dr. Ursula von der Leyen at her inauguration 3 DEC 2019: one of two priorities is to reduce carbon emission to 1950 level. **<u>Change of thousands of power stations</u>**

<u>NUCLEAR REACTION ENERGY is 10 Million times higher than chemical</u>

Environmentally sufficiently clean HB11 boron fusion instaed of DT fusion:

$$^{11}B + p \rightarrow 3\alpha + 8.7\ \text{MeV}$$

First investigation:

Oliphant & Rutherford, L. Proc. R. Soc. London A 141 (1933) 259

Interest for future CLEAN nuclear fusion reactors:

Rostoker et al, Science 278 (1997) 1419

Hora Miley et al, Energy Environ. Sci. 3 (2010) 479, …Hora…Mourou Laser Part. Beams 33(2015) 607 –Fig 16;

Laser Experimental studies per laser shot:

Belyaev et al. Phys. Rev. E 72 (2005) 026406, yield ~ 10^3

Labaune et al. Nature Comm. 4 (2013) 2506, yield ~ 10^7

Picciotto et al. Phys. Rev. X 4, 031030 (2014), yield ~10^9 p/Sr

Giuffrida et.al.Phys. Rev.E 101 013204 (2020),yield~10^{10}p/Sr

highlights

Eliezer et al. Phys. Plasmas 23 (2016) 050704, Avalanche proton-boron fusion explains measured Gain close to DT at comparable conditions.

D. Margarone S. Fujioka et al. Osaka SEP. 2020 confirming the PALS-iodine Jan 2020 of 10^{10} HB11 fusion reactions, but using now contrast-correct CPA-PW pulses resulting in same gain

Nuclear Fusion at thermal eqilibrium

<u>pressure p needs</u> temperatures of >100Millions of °C

Sun: fusion of hydrogen to helium: >15Million degrees

Fusion in Stellarator 1980: 10Million degrees: DD fusion

<u>**Reached**</u> in tokamaks and NIF <u>**but no breakeven yet (too short)**</u>

<u>A: FUSION IGNITION AT MODEST TEMPERATURE & NON-LTE??: no local thermal equilibrium and LASERS:</u>

NON-LINEARITIES

Plasma parameters

Force density in Plasmas: thermal pressure p

$$\mathbf{f} = -\nabla p$$

With **LASER: non-thermal nonlinear force** $\mathbf{f}_{NL}$

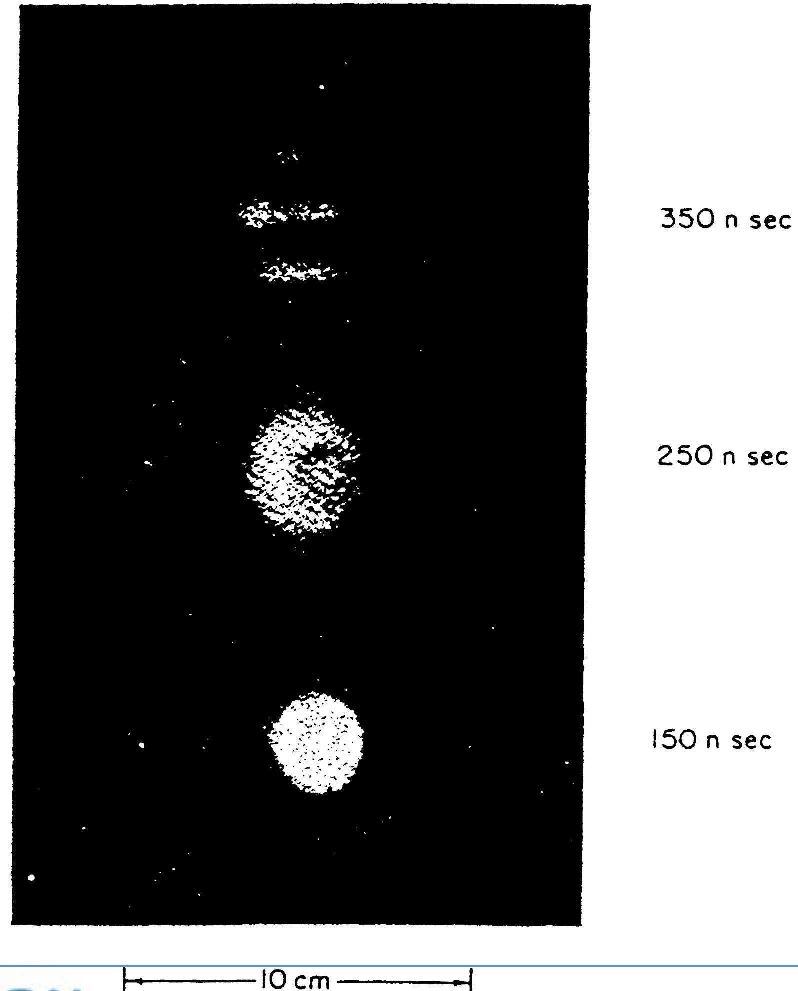
$$\mathbf{f} = -\nabla p + \mathbf{f}_{NL}$$

HB11 ENERGY

Plasma parameters

Laser driven plasma :Thermal (core) versus Nonlinear (half moono) 1968 explained in Fig. 2.5 of Laser Plasma Physics (Hora 2016) Westinghouse Sucov et al 1967

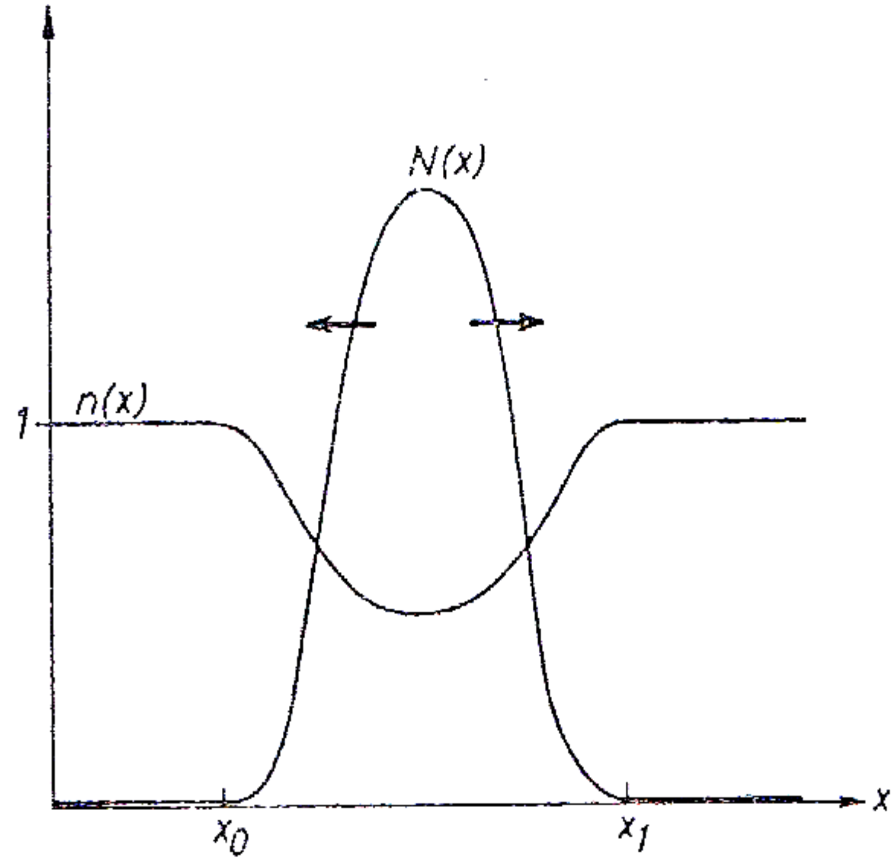
Visible nonlinear force acceleration: >keV ions without 10 Million ° C temperature



Central spherical plasma with classical thermal expansion in the range of dozens of eV temperature. Halfmoon plasma with >keV ions accelerated by nonlinear force, not by keV temperature. Its low temperature is a typical non-thermal process, **definitely not with a keV bremsstrahlung emission**

Plasma parameters

A laser pulse arriving from the left hand side on a plasma slab of density N(x) with the schematic drawn curve for the optical constant n(x). Nonlinear forces (arrows) are tearing the slab into blocks moving against the laser beam and another in the beam direction**: nonlinear force driven DIELECTRIC EXPLOSION of plasma block acceleratin**



Force in plasma

$$\mathbf{f} = -\nabla p + \mathbf{f}_{NL}$$

Presure p by temperture T

Nonlinear force

$$\mathbf{f}_{NL} = -\nabla\bullet[\mathbf{EE} + \mathbf{HH} - (\mathbf{E}^2 + \mathbf{H}^2)\mathbf{1}/2$$
$$+ (1+(\partial/\partial t)/\omega)(\mathbf{n}^2-1)\mathbf{EE}]/(4\pi)$$
$$- (\partial/\partial t)\mathbf{E}\times\mathbf{H}/(4\pi c) \qquad (1969;1985)$$

Simplfied geometry (1967)

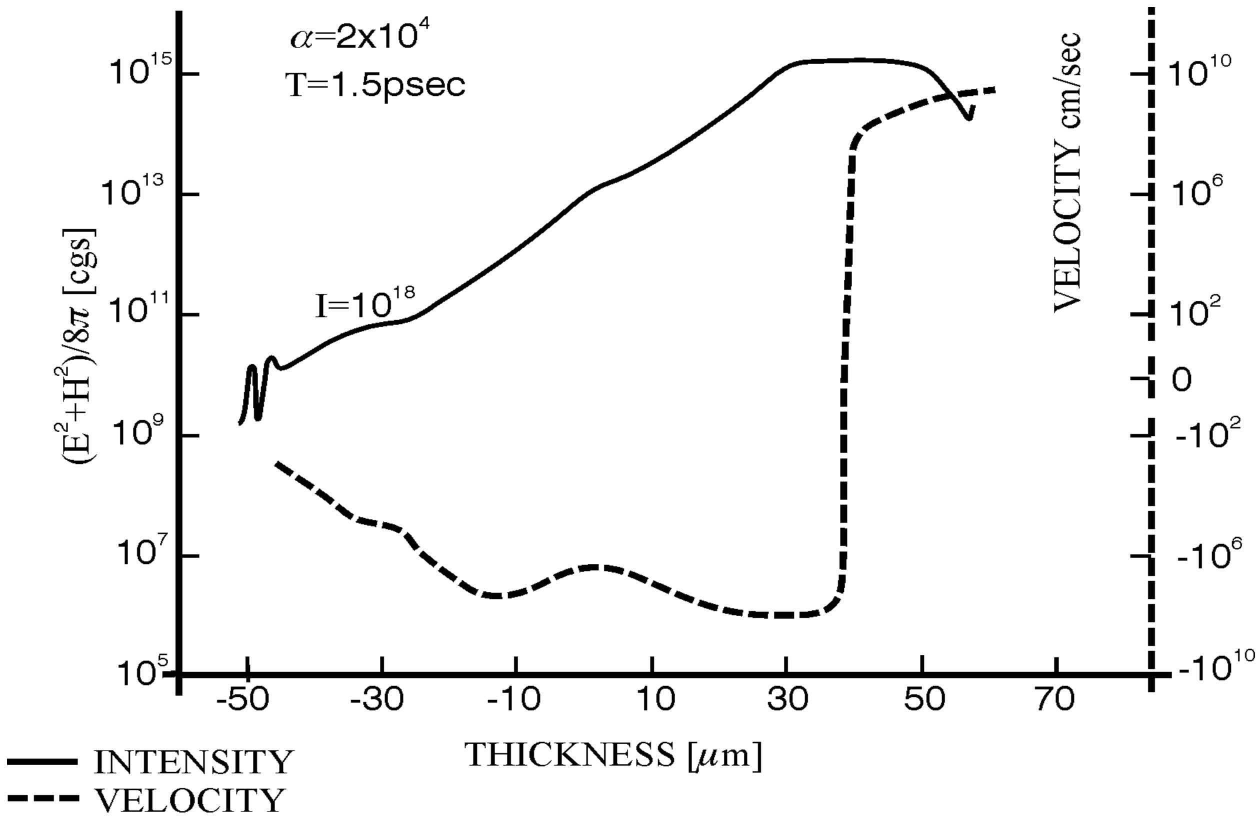
$$\mathbf{f}_{NL} = -(\partial/\partial x)(\mathbf{E}^2+\mathbf{H}^2)/(8\pi)$$
$$= -(\omega_p/\omega)^2(\partial/\partial x)(E_v{}^2/\mathbf{n})/(16\pi)$$

Kelvin's ponderomotion 1845. Maxwell's Stress tensor

Plasma refractive index

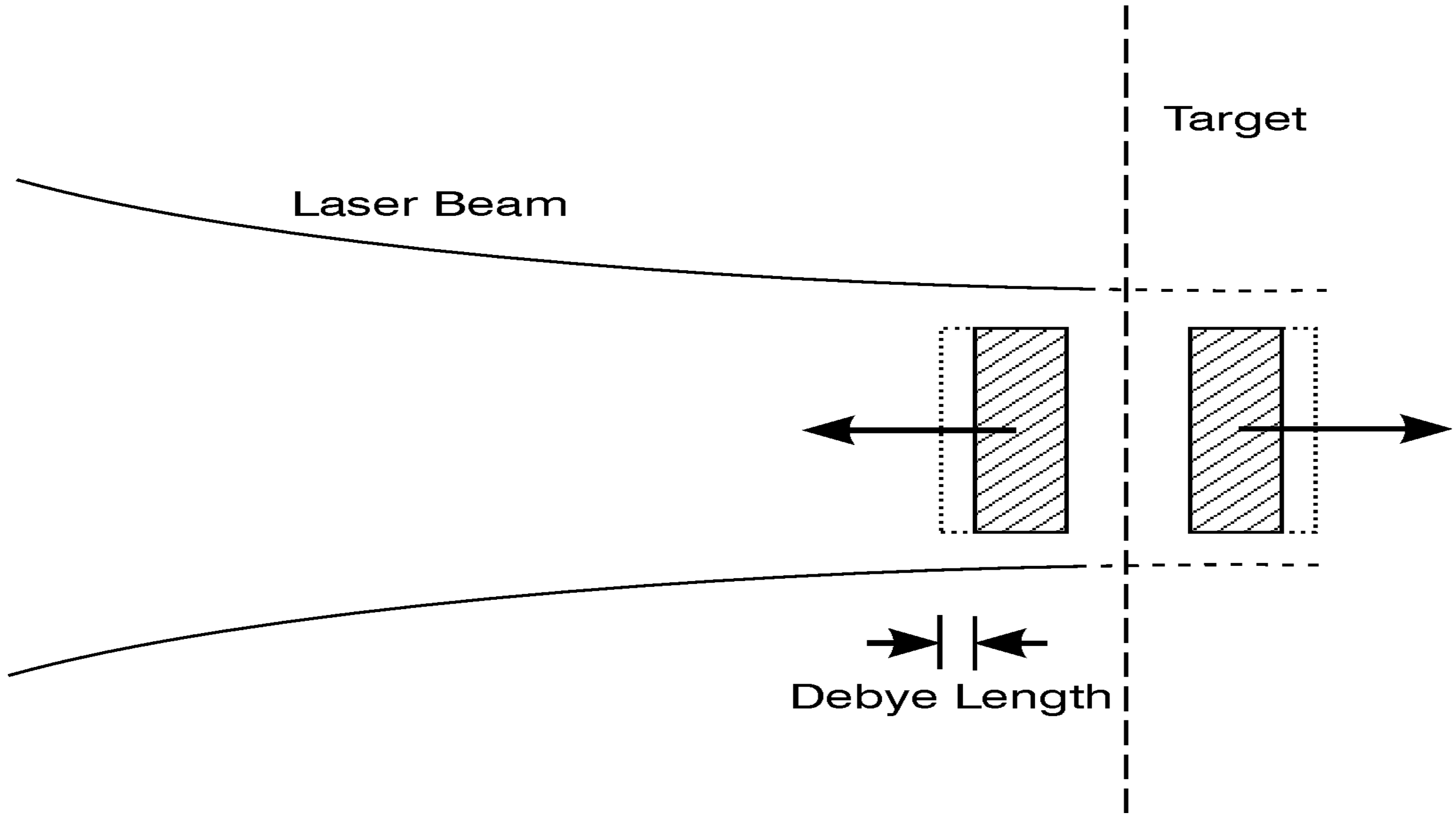
$$\mathbf{n} = 1 - (\omega_p/\omega)^2/(1 - i\nu/\omega); \quad \omega_p{}^2 = 4\pi e^2 n_e/m$$

Plasma parameters

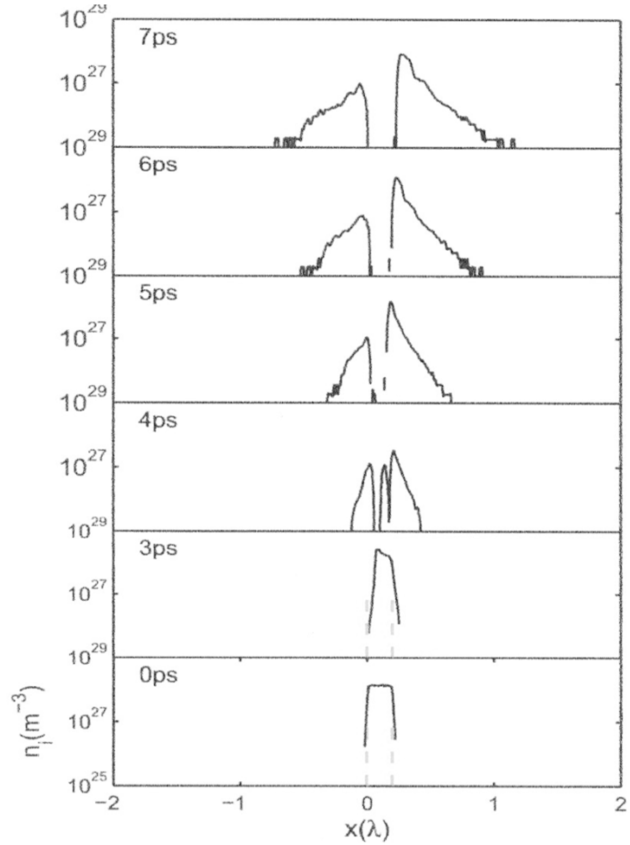


Numerical results: plane geometry, Bi-Rayleigh initial boron keV density (**1978**):

Ultrahigh acceleration **of deuterium after 10^{18} W/cm^2 irradiation 1.5ps: >10^{20} cm/s^2**



directed **plasma blocks**, space charge neutral with ion current density $j > 10^{14}$ Amps/cm^2 **(AVOID RELATIVISTIC SELFFOCUSING: Jie Zhang et al 1998)**



Spatial distribution of the electron and ion densities under differer
ter an intense laser pulse is injected upon a solid-density plasma. Th
tensity $I_0 = 10^{15}$ W/cm^2, wavelength $\lambda = 0.4$ μm, and pulselengt
ps. The plasma density $n_0 = 2n_c = 1.392 \times 10^{28}$ m^{-3}, where n_c i
cal plasma density, and the plasma thickness is 0.2λ. The dashed lin

NON-HYDRODNAMIC PIC COMPUTATION OF DIELECTRIC NONLINEAR FORCE DRIVEN PLASMA EXPLOSION TO GENERATE BLOCKS: PLASMA DENSITY N DEVELOPMENT (SOFE 2017 HORA, ELIEZER, JIAXIANG WANG ET AL. BLOCK MOVING AGAINST LASER BEAM, BLUE DOPPLER SHIFT OF SPECTRAL LINES. IEEE TRANSACT. PLASMA SCIENCE 46 (2018) 1191

FIRST MEASUREMENT ULTRAHIGH ACCELERATION OF PLASMA BLOCK

>10^{20}cm/s^2 FROM DOPPLER BLUE SHIFT:

R. SAUERBREY, Phys. Plasma 3 (1996) 4712

Repetition:

I. Földes et al. Laser Phys. 10 (2000) 264

Necessary: **very high contrast ratio** of <ps CPA pulses
(Jie Zhang et al. Phys.Rev.57 (1998) 3745)

Nonlinear-force-driven plasma-block ignition has been theoretically and numerically predicted and was experimentally confirmed. Example of numerous numerical studies about shock processes and plane geometric fusion details using the genuine two-fluid hydrodynamics show internal electric fields and later fusion reactions (Hora, Lalousis, Eliezer, Physical Rev. Letters 53 (1984)1650.

1) Hora, P Lalousis, L Giuffrida, D Margarone, G Korn, S Eliezer, G H Miley, S Moustaizis, G Mourou and C P J Barty. Picosecond-petawatt laser-block ignition for avalanche fusion of boron by ultrahigh acceleration and ultrahigh magnetich fields. Journal of Physics Conf. Proceed. 717 (2016) 012024

2) Paraskevas Lalousis, Heinrich Hora, Shalom Eliezer, Jose-Maria Martinez-Val, Stavros Moustaizis , George H. Miley & Gerard Mourou. Shock mechanisms by ultrahigh laser accelerated plasma blocks in solid density targets for fusion. Physics Letters A, **377**, 885-888 (2013).

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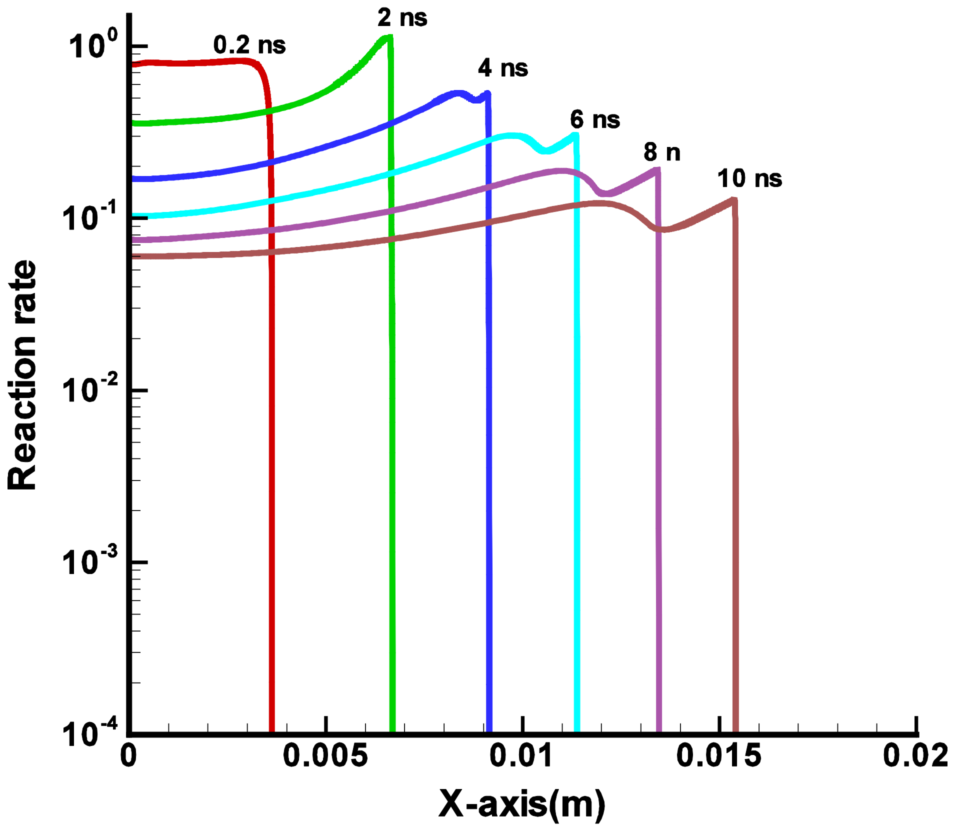
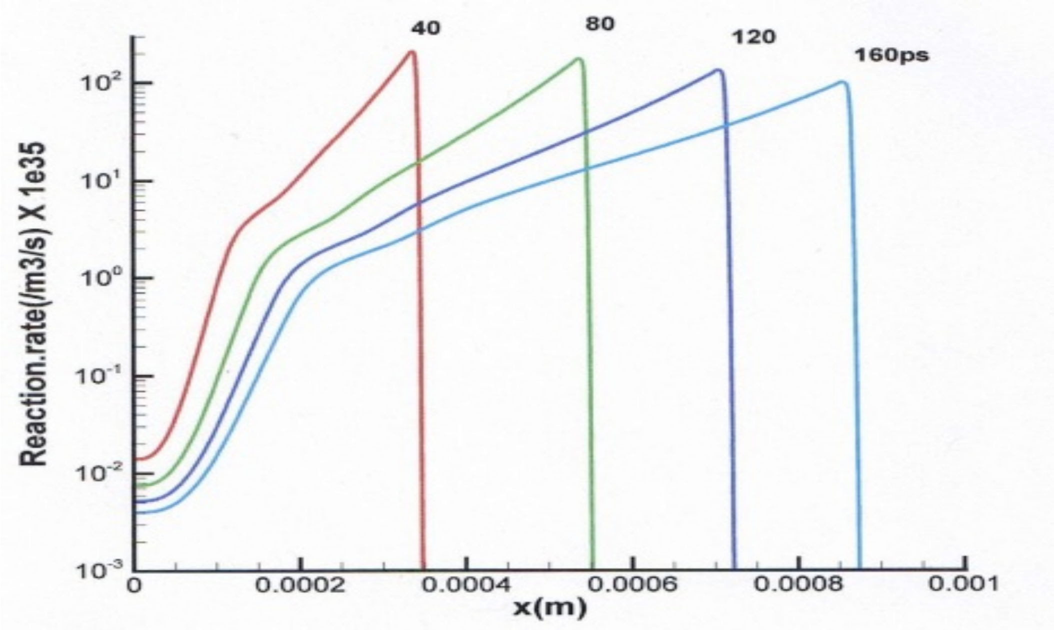
Example of large number of computations of plane DT wave fusion gain computations.similars for B11



Reaction rates (to be multiplied by 10^{36} $m^{-3}s^{-1}$) in solid DT at 1 ps pulse of energy flux E*= 3×10^8 J/cm^2 KrF laser irradiation depending on the fuel depth x at different times up to 10 ns (Lalousis et al. 2013).

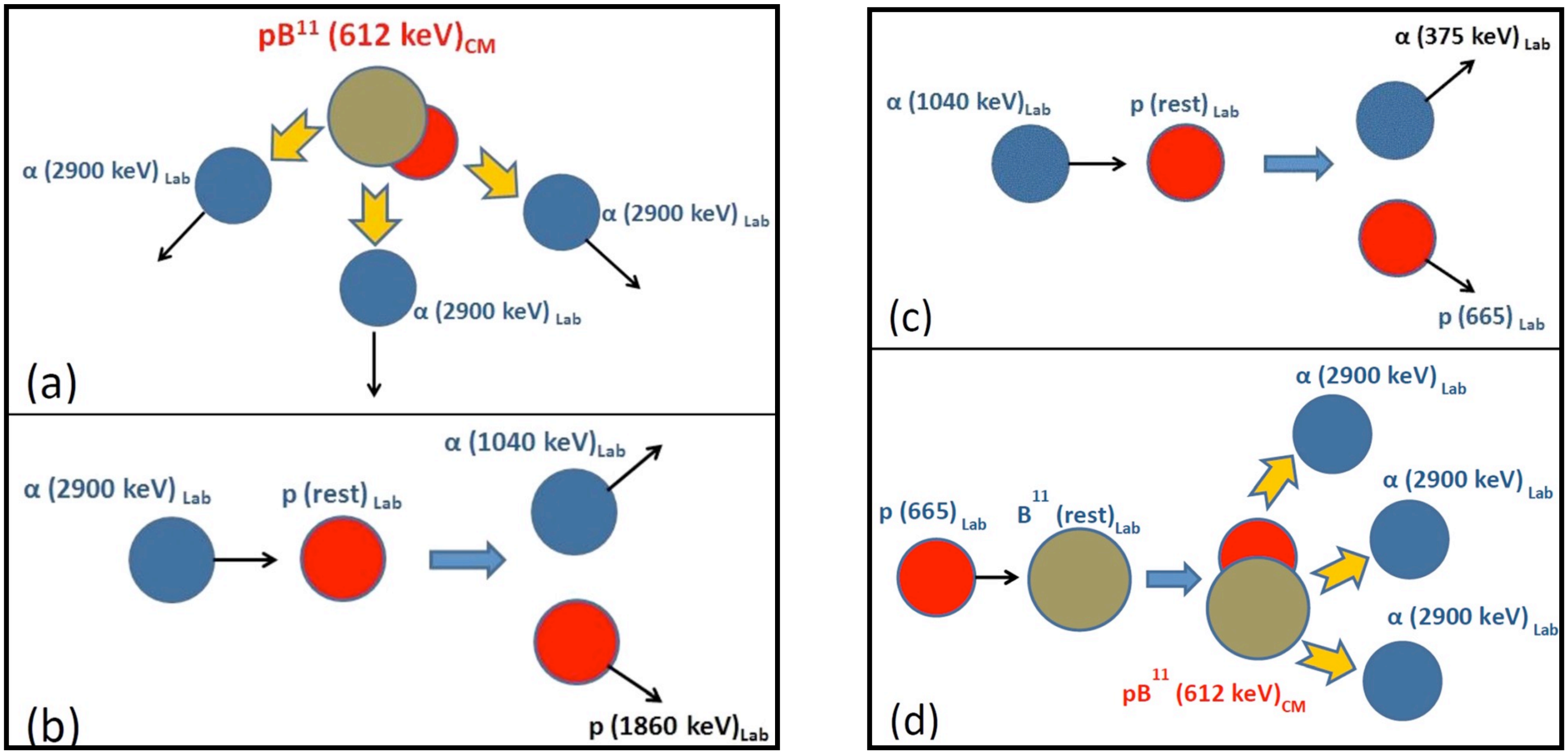
HB11 fusion reaction rates from genuine 2-fluid Hydro-computations. Reaction (collisions included detailled Rankine-Hugoniot shock front)



HB11 fusion reaction rate at different depths x in 1-D computation parallel to the magnetic field, at times after the ps generation of the fusion flame initiated by 10^{20} W/cm^2, ps, 248-nm wave-length laser pulse. Estimated a considerable amount of fuel has been burned.

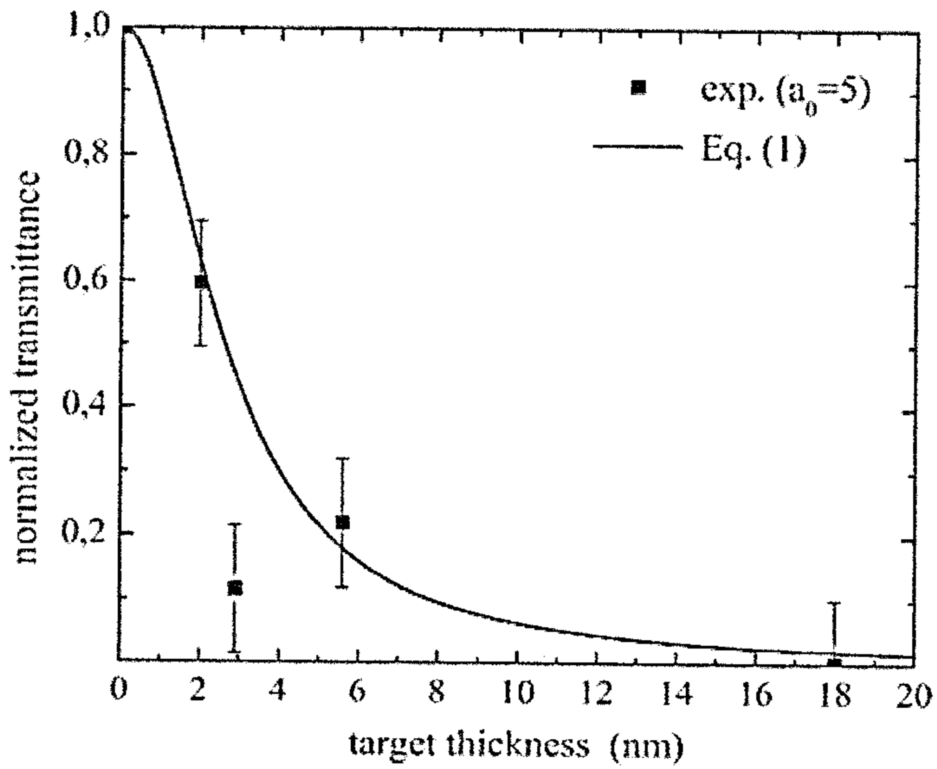
The yield of α particles can be enhanced by avalanche scheme:

Since the hydrogen density is larger than the boron density, a new chain of reactions can be get as shown in Figure . While E_{cm}(pB11) is the center-of-mass system energy of that boron and a proton at rest in the lab frame.



Eliezer et al. Phys. Plasmas 23 (2016) 050704.

Plasma parameters



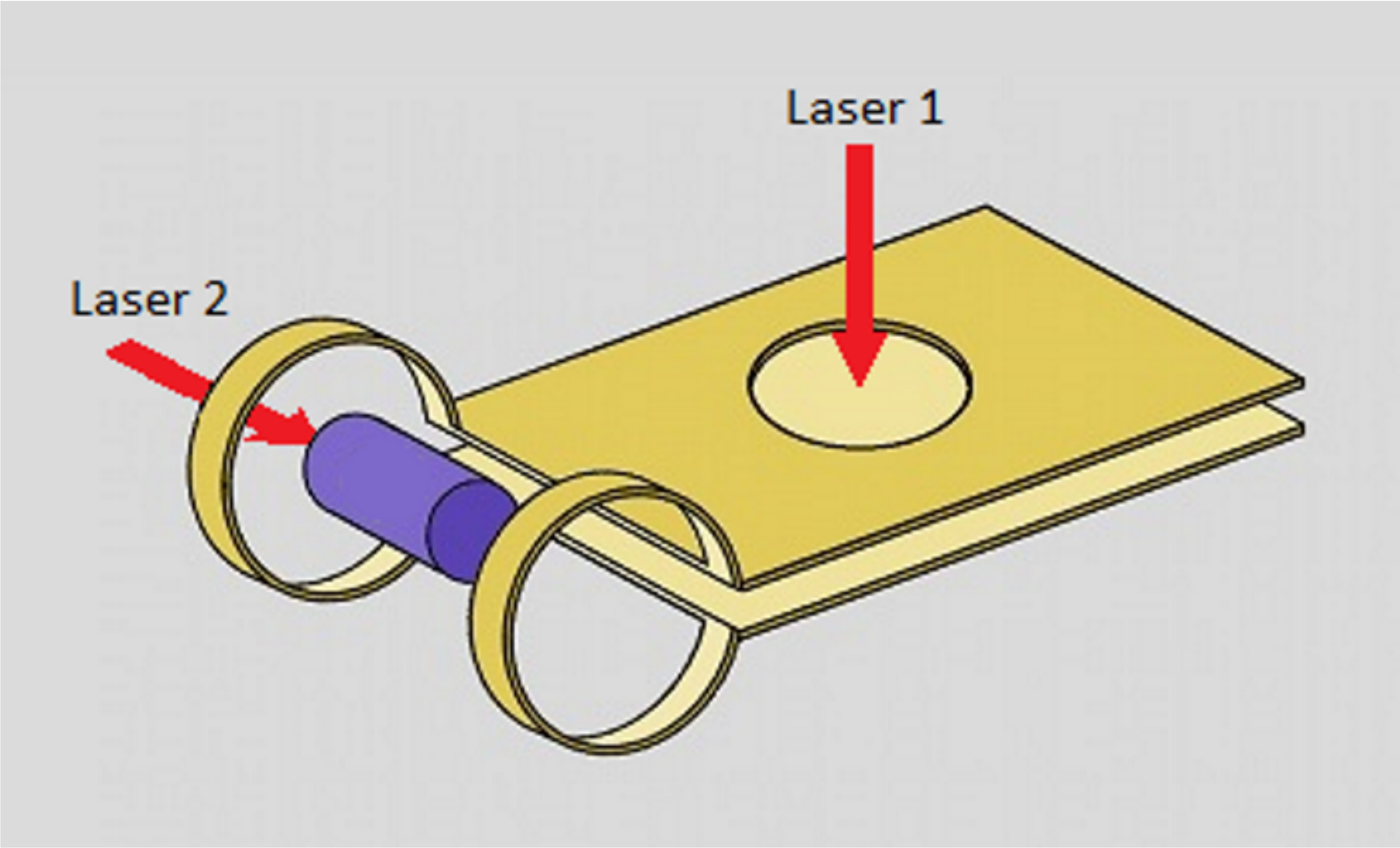
Steinke et al. Experiment: 18nm diamond films: Laser & Part. Beams 28 (2010) 16

CPA laser pulse produces >10^{12} Joule/cm^3 energy density fully absorbed in 18nm . This is much more than from thermal pressures in HB11 fusion of solid density fuel at billion ^{o}C.

Fujioka et al (2013) **Capacitor-coil eperiment**

4 kilotesla magnetic field by 30PW-ps laser pulse 2

REACTION UNIT IN CENTER OF COIL



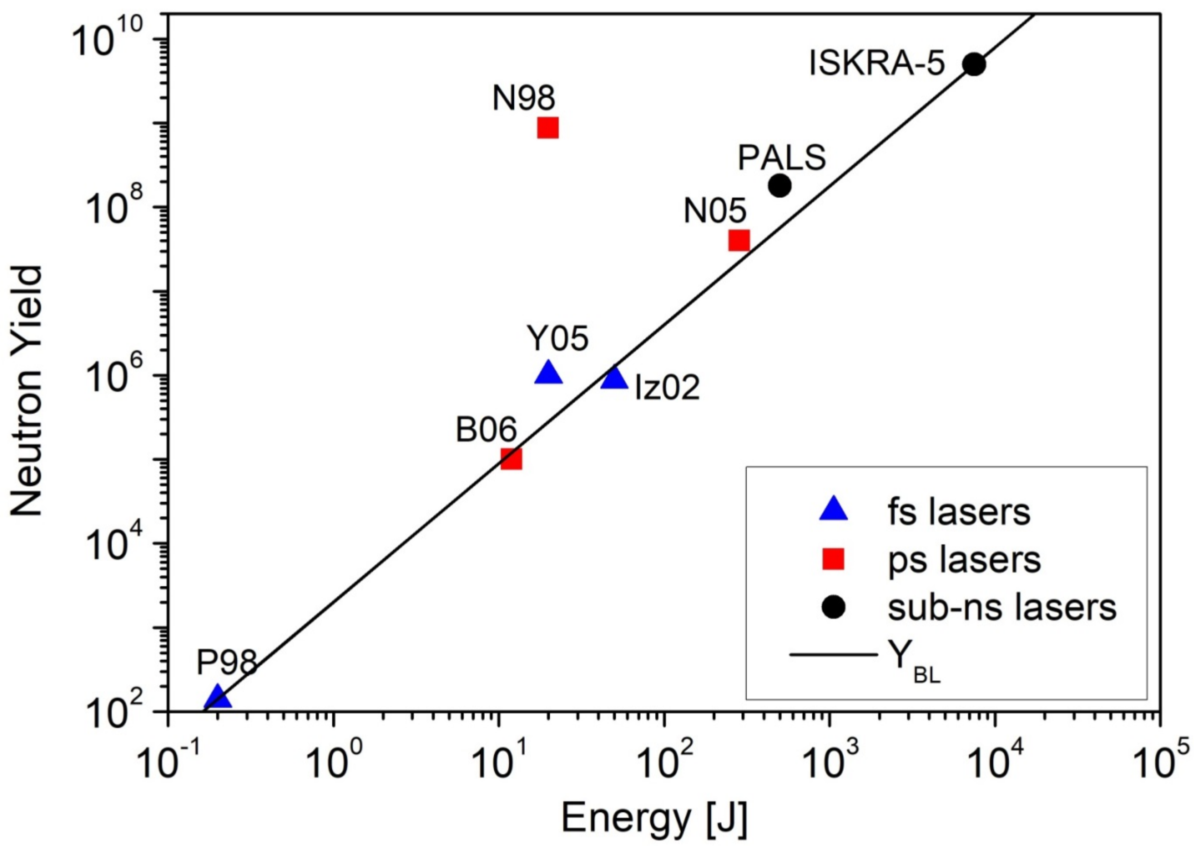
Steinke et al. Experiment: 18nm diamond films

[Laser & Part. Beams 28 (2010) 16]

CPA laser pulse produces >10^{12} Joule/cm^3 energy density. This is much more than from thermal pressures for analogeous case in HB11 fusion of solid density fuel at billion ^{o}C. Energetic ion emission was measured but more details with more data are needed for conclusions.

(see Press/Publications, entry May 2019 of website "HB11 Energy" S. Eliezer, H.Hora, G.H.Miley, G.K. Kirchhoff, W. McKenzie, J. Kirchhoff and N. Nissim , Environmentally Clean Energy from Laser Boron Fusion using CPA pulses)

Net energy gain



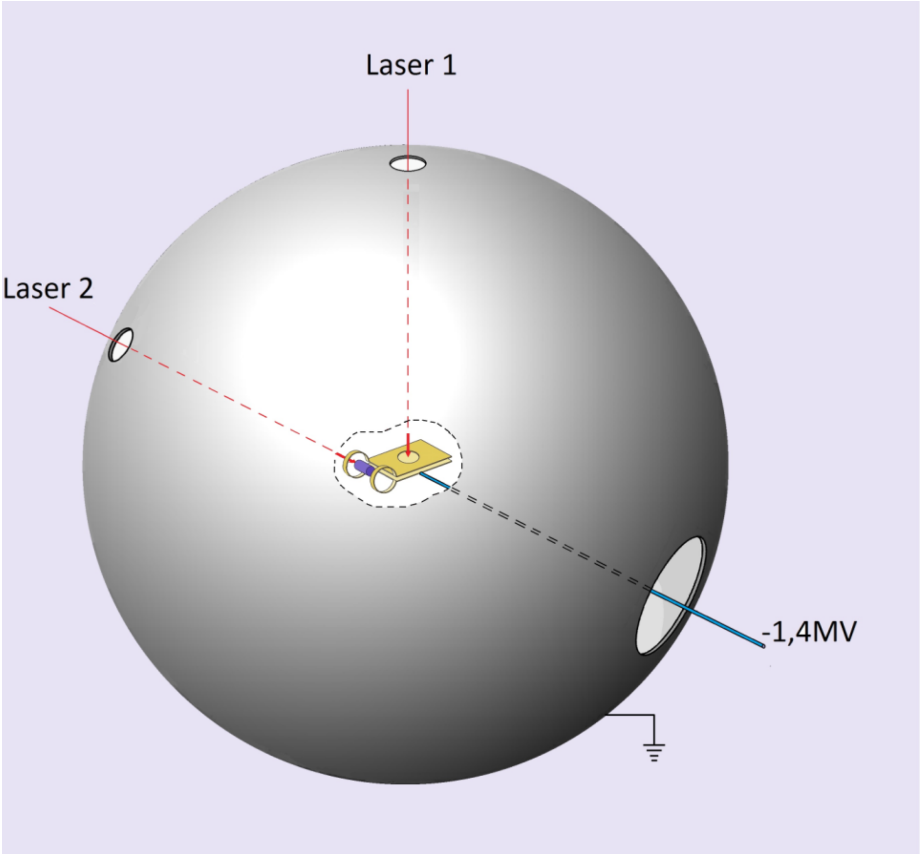
Krasa et al. (2013): **measured 10,000 times higher DD fusion reactions** by non-thermal plasma block ignition than by thermal equilibrium as calculated for HB11 at ps lasers. Hora et al. High Energy Density Physics 35 (2020) 100739

DD Neutron measurement with PW pulses with diagrams of Krasa et al. Obliqe line for thermal ignition. Jump from Belyaev BO6 to Norreys N98 for ps pulses: **ten thousand more reactions** (now with measuements in Austin and Korea: Xuejing Jiao PhD 2019.....Hegelich....

Change from thermal and non-thermal initiation of fusion reaction conditions for pc pulses:

vertical Krasa-line

DESIGNNG
OF PROTON-BORON LASER FUSION REACTOR



The central reaction unit is electric charged to the level of −1.4 MV against the wall of a sphere producing α-particles of more than a GJ energy, of which a small part is needed for the operation of the laser pulses. One part of the gained costs of electricity is needed for the apparatus of the central reaction and for the boron hydrid of the fuel being destroyed at each reaction (co-author: Gerard Mourou)

Scheme of an economic electric power reactor for production of boron-fusion, absolutely free from the problem of dangerous nuclear radiation (Hora et al., 2014, 2015) with the estimated possibility of an environmentally clean, high efficiency power station (**Hora et al., Laser and Particle Beams 35 (2017) 730**) granted patent in US, China, Japan UK,...

HB11 fusion gains with PALS Iodine laser (Giuffrida et al. Phys. Rev. Jan. 2020). Repeated with correct contrast ps-PW CPA-Laser Pulses at ILE-Osaka (Margarone, Fujioka et al) Sept. 2020

PHYSICAL REVIEW E **101**, 013204 (2020)

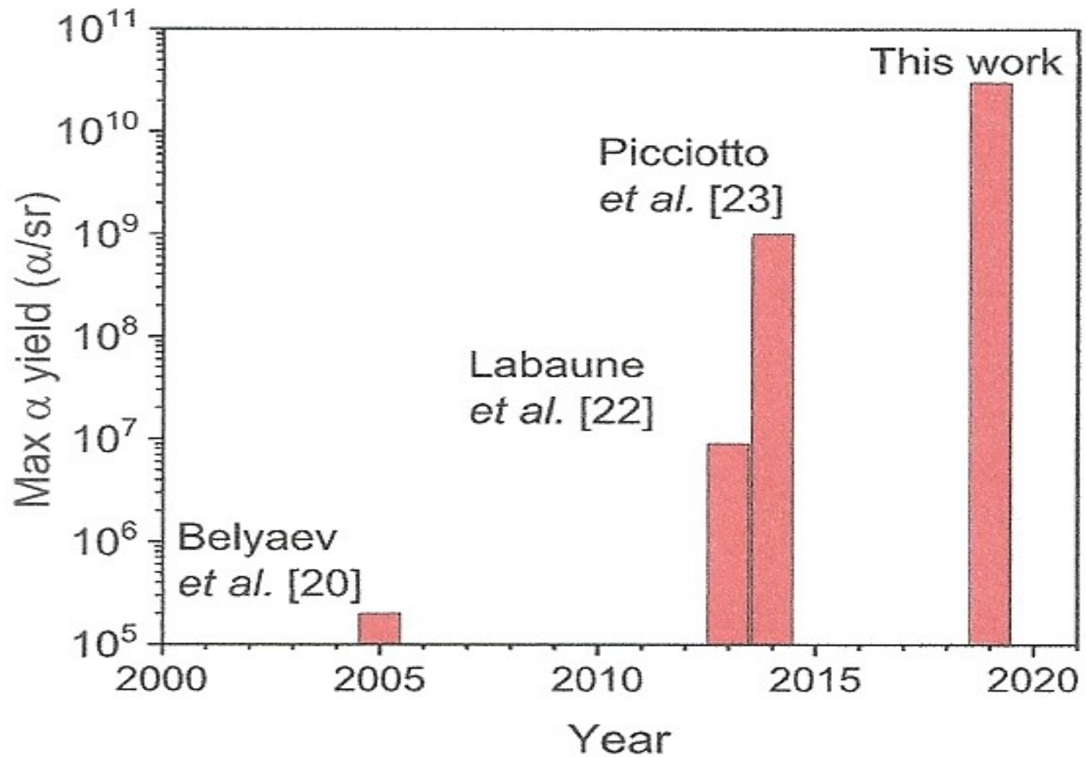


FIG. 9. Progression of the most important experimental achievements reported in the literature in terms of maximum α particles/sr.

CONCLUSIONS

First energy densities $>10^{12}$J/cm^3 were reached in diamond aiming in analogy to ignite HB11 nuclear fusion by non-thermal pressures of more than dozens of million°C.

Pressures needed by nonlinear forces from picosecond laser CPA-laser pulses above petawatt (30 PW) power are about state of the art.Ultrahigh acceleration of plasma blocks was measured by dielectric explosion (different from radiation pressure acceeration) as predicted from non-thermal interaction.

Environmentally clean, free from nuclear meltdown, and low cost electricity generator from abandon boron fuel was designed. The expected energy gain is based on boron-hydrogen reaction at CPA end-on cylinder ignition from magnetic trapping by extreme capacitor-coil kTesla fields.

Main result:

Problem needing the dozens of millions ^{o}C temperatures for thermal pressures for nuclear fusion is **eliminated** by using the **non-thermal pressure of the nonlinear forces by CPA laser pulses**

What has been achieved:

1) Fusion ignition **non-thermal** with pressure from CPA laser pulses. Get rid of dozens of million degrees Celsius temperatures > 10 PW pulses every few seconds.
2) **Clean** energy gains of HB11 measured similar to DT: free from primary nuclear radiation and elimination of secondary neutrons by **neutron caption**.
3) Break-even by **dielectric explosion** of nonlinear-force driven plasma blocks only with **blue Doppler** shift in contrast to ordinary radiation pressure with red shift.
4) Aiming to have **low cost, absolute clean, safe and abundant electricity** from laser boron fusion.

Journal of Energy and Power Engineering 14 (2020)

doi: 10.17265/1934-8975/2020.05.003

For downloading

Journal of Energy and Power Engineering 14 (2020)

doi: 10.17265/1934-8975/2020.05.003

Extreme CPA laser pulses for igniting nuclear fusion of hydrogen with boron-11 by non-thermal pressures for avoiding ultrahigh temperatures

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