This talk is evolved from a Hungarian Academy of Science inaugural presentation on June 13th, 2022

CXCV Conventui Generali
Academiae Scientiarum Hungaricae
seu Conventui academicorum
visum est
virum doctissimum

Johann Rafelski
de disciplina physicae

Sodalem Honoris Causa
creare.

Sodalibus honoris causa inde a quo creati sunt tempore,
id est a die III mensis Maii anni MMXXII,
omnia competunt iura civili de Academia lege collata
ipsiusque Academiae statutis et Ordine stabilita,
atque ab eodem die contentis inibi tenentur officiis.

Budapestini, die III mensis Maii, anni MMXXII.

Academiae Scientiarum Hungaricae
Praeses

(az Akadémikusok Gyűlése)

Johann Rafelski
professzor urat

a fizika kutatása
terén kifejtett kiemelkedő tudományos tevékenysége elismeréséül
a Magyar Tudományos Akadémia

tiszteleti tagjává választja.

A tiszteleti tagot az akadémikussá választás időpontjától
(2022. május 3.) megilletik az akadémiai törvényben, valamint
az MTA Alapszabályában és Ügyrendjében meghatározott jogok,
és ezen időponttól köteles eleget tenni az azokban meghatározott
kötelezettségeknek.

Budapest, 2022. május 3.

a Magyar Tudományos Akadémia
elnöke

Unification of QGP and fusion communities at the first Vacuum Structure Particles and Plasmas Budapest Symposium

POLAK, WĘGIER, DWA BRATANKI I DO SZABLI, I DO SZKLANKI

Searching for Viable Paths to Nuclear Fusion Energy

Johann Rafelski

THE UNIVERSITY OF ARIZONA

Department of Physics

Presented at the XI International Conference on New Frontiers in Physics September 8th, 2022

Liberty Square, Budapest

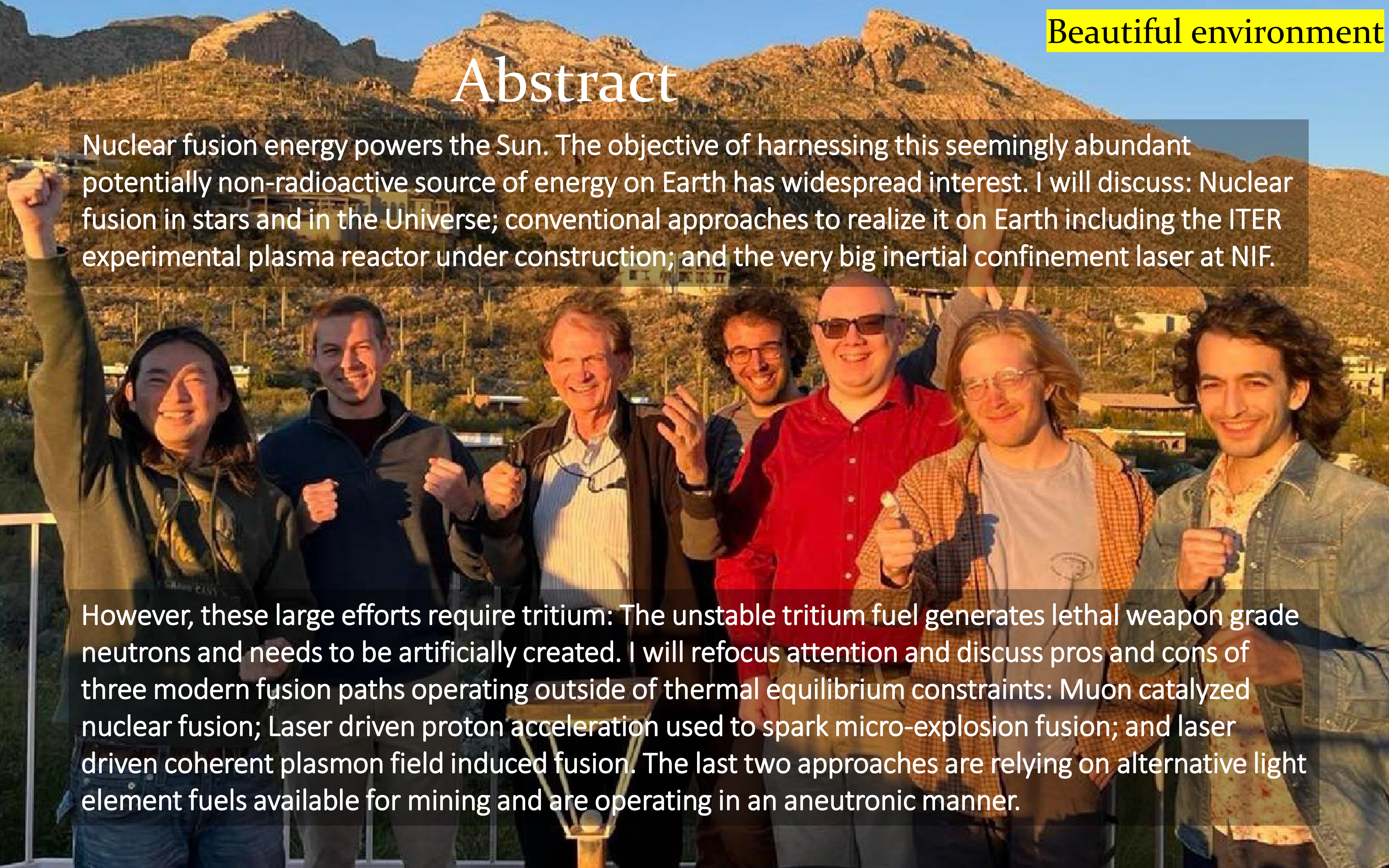
Budapest; Photo by László Pál Csernai

Beautiful environment

Abstract

Nuclear fusion energy powers the Sun. The objective of harnessing this seemingly abundant potentially non-radioactive source of energy on Earth has widespread interest. I will discuss: Nuclear fusion in stars and in the Universe; conventional approaches to realize it on Earth including the ITER experimental plasma reactor under construction; and the very big inertial confinement laser at NIF.

However, these large efforts require tritium: The unstable tritium fuel generates lethal weapon grade neutrons and needs to be artificially created. I will refocus attention and discuss pros and cons of three modern fusion paths operating outside of thermal equilibrium constraints: Muon catalyzed nuclear fusion; Laser driven proton acceleration used to spark micro-explosion fusion; and laser driven coherent plasmon field induced fusion. The last two approaches are relying on alternative light element fuels available for mining and are operating in an aneutronic manner.



My fusion credentials

- 1973: PhD from Frankfurt University with specialty in **theoretical nuclear physics**
- 1978, 1985 – 1992: Muon-catalyzed fusion
- 2011 – 2015: pB fusion and lasers
- 2021 – present: Moving into plasmonic fusion

nature COMMUNICATIONS

Received 24 Jan 2013 | Accepted 27 Aug 2013 | Published 8 Oct 2013 DOI: 10.1038/ncomms3506

Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

C. Labaune[1], C. Baccou[1], S. Depierreux[2], C. Goyon[2], G. Loisel[1], V. Yahia[1] & J. Rafelski[3]

HYDROGENIC MESOMOLECULES AND MUON CATALYZED FUSION

J. Rafelski

CERN -- Geneva

A B S T R A C T

Hydrogenic mesomolecules are discussed with particular emphasis on their rôle in the μ catalyzed fusion process. Recent theoretical and experimental evidence for weakly bound mesomolecules ddμ and dtμ derived from resonant mesomolecular formation and its dependence on the temperature is described. The fate of the muon stopped in dense hydrogenic target is followed as well as that of a muon sticking to the fusion product.

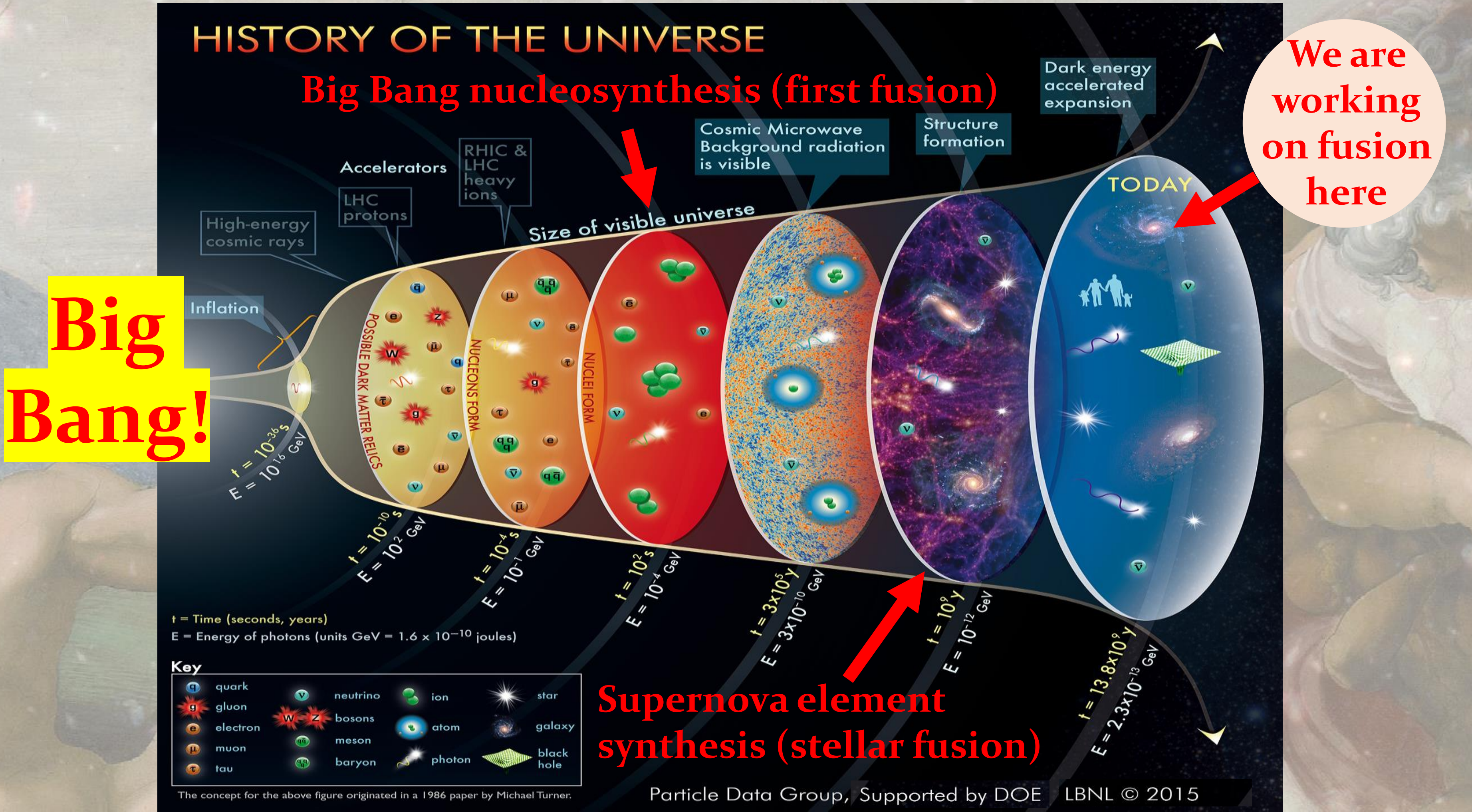
Lectures at the International School of Physics of Exotic Atoms, Erice

25 March -- 5 April 1979

Ref.TH.2679-CERN

8 June 1979

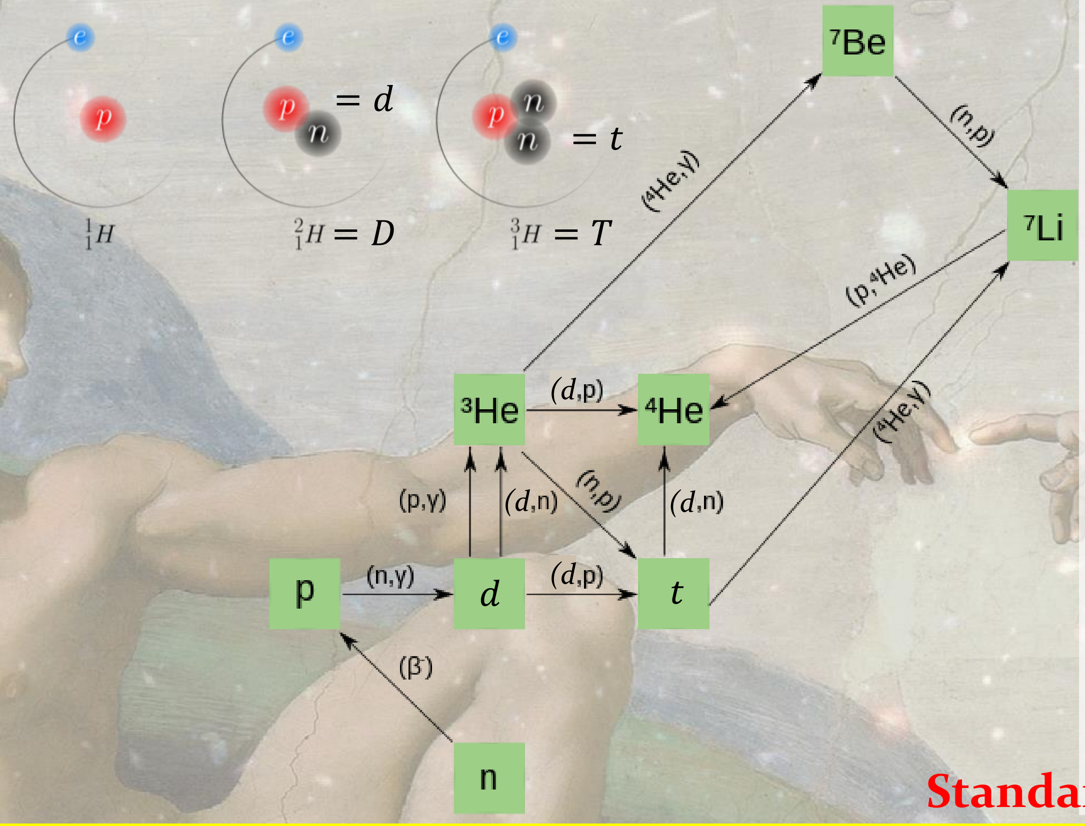
Matter in the Universe: Making nuclei

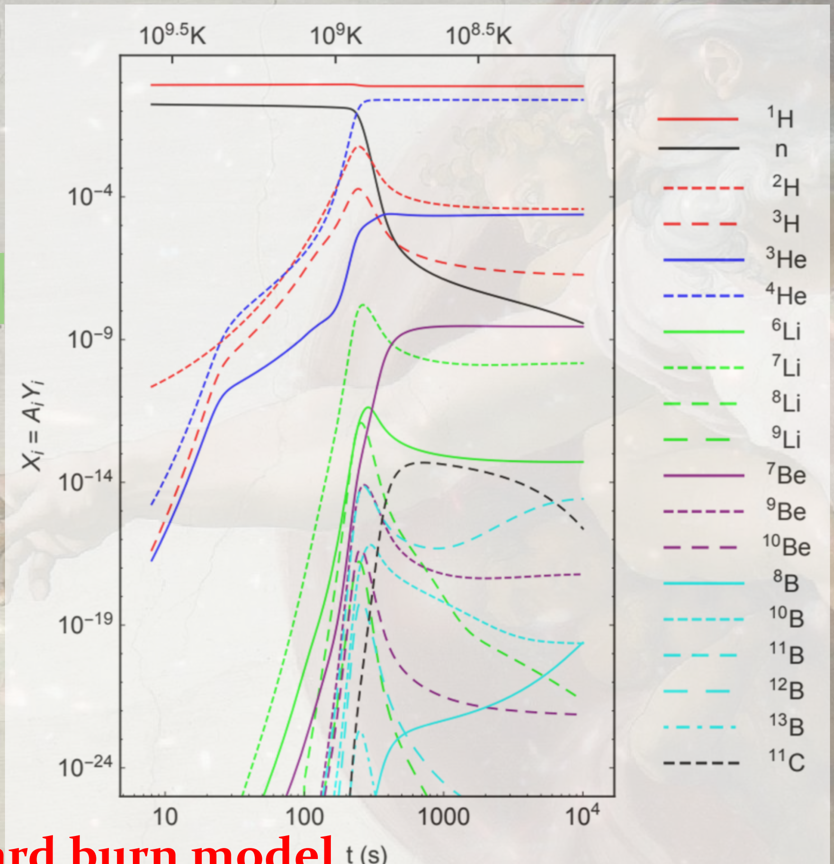


The first nuclear burn in the universe: Big Bang nucleosynthesis

BBN is responsible for the generation of the light elements in the early Universe while heavy elements are products of stellar evolution.

BBN, unlike stellar burn, has neutrons available with a life-time of 880 seconds.



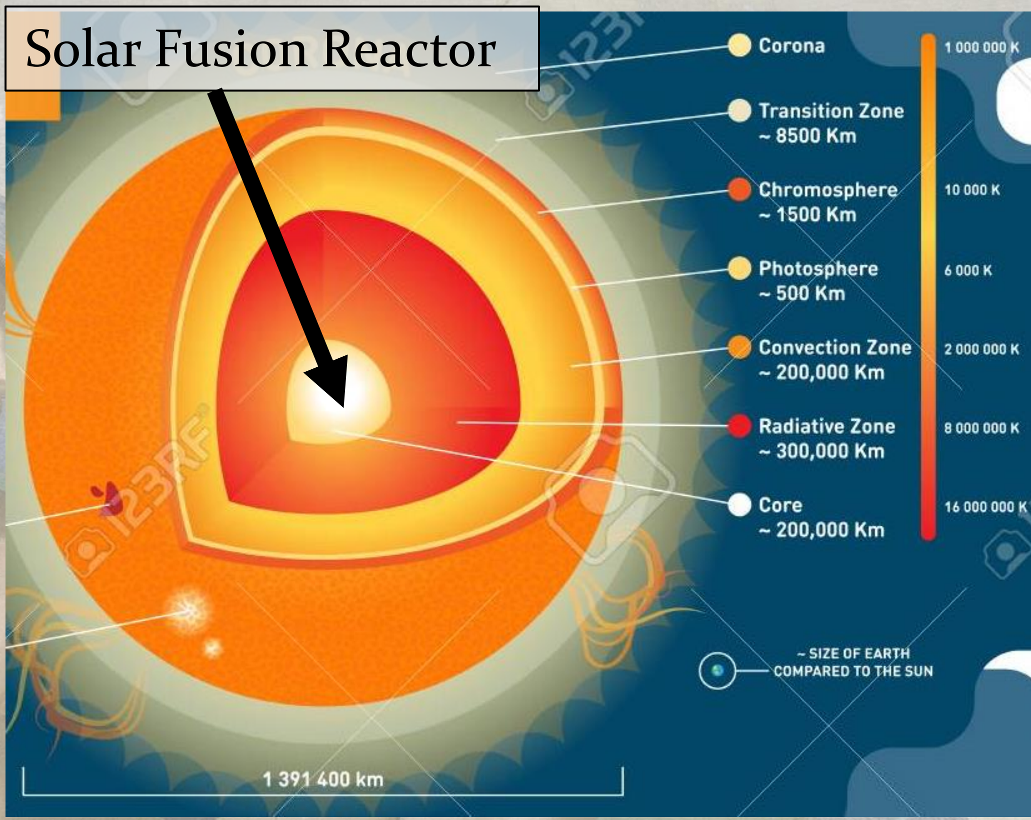


Standard burn model

C. Pitrou, et al. "Precision big bang nucleosynthesis with improved Helium-4 predictions." Physics Reports 754 (2018): 1-66.

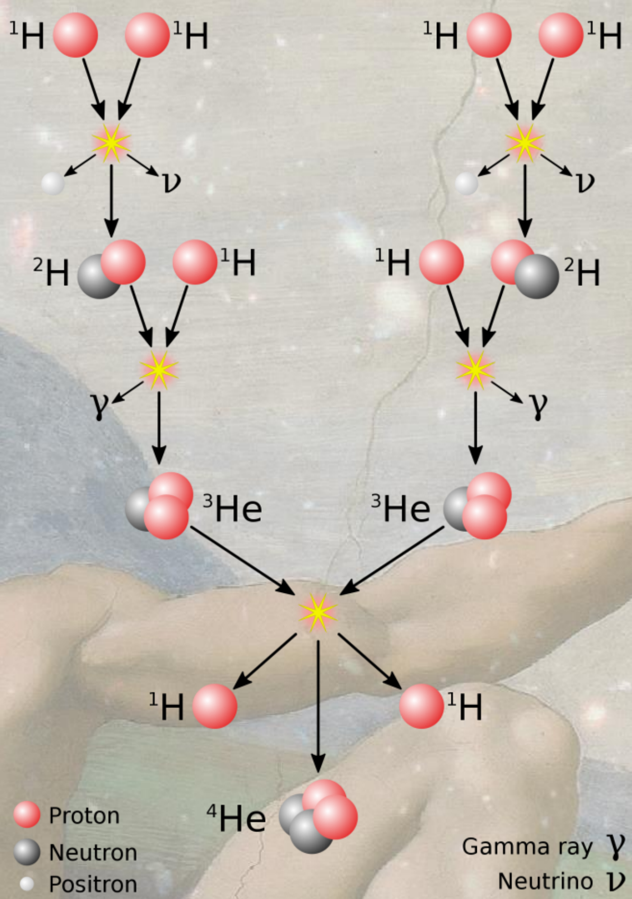
The fusion reactor powering the solar system

The sun is primarily made up of primordial hydrogen and helium.



- The Sun produces energy by converting hydrogen into helium-4. Two processes are well known:
  - Proton-Proton (PP) chain
  - Carbon-Nitrogen-Oxygen (CNO) cycle
- Gravity provides the confining force which balances the explosive radiative pressure.
- It produces 3.8×10^{26} W and has been continuously running for 4.6 billion years.
- The Earth is habitable by the grace of our "local" **stable** Solar core fusion nuclear reactor.

Primary power source of our Sun: The proton-proton chain

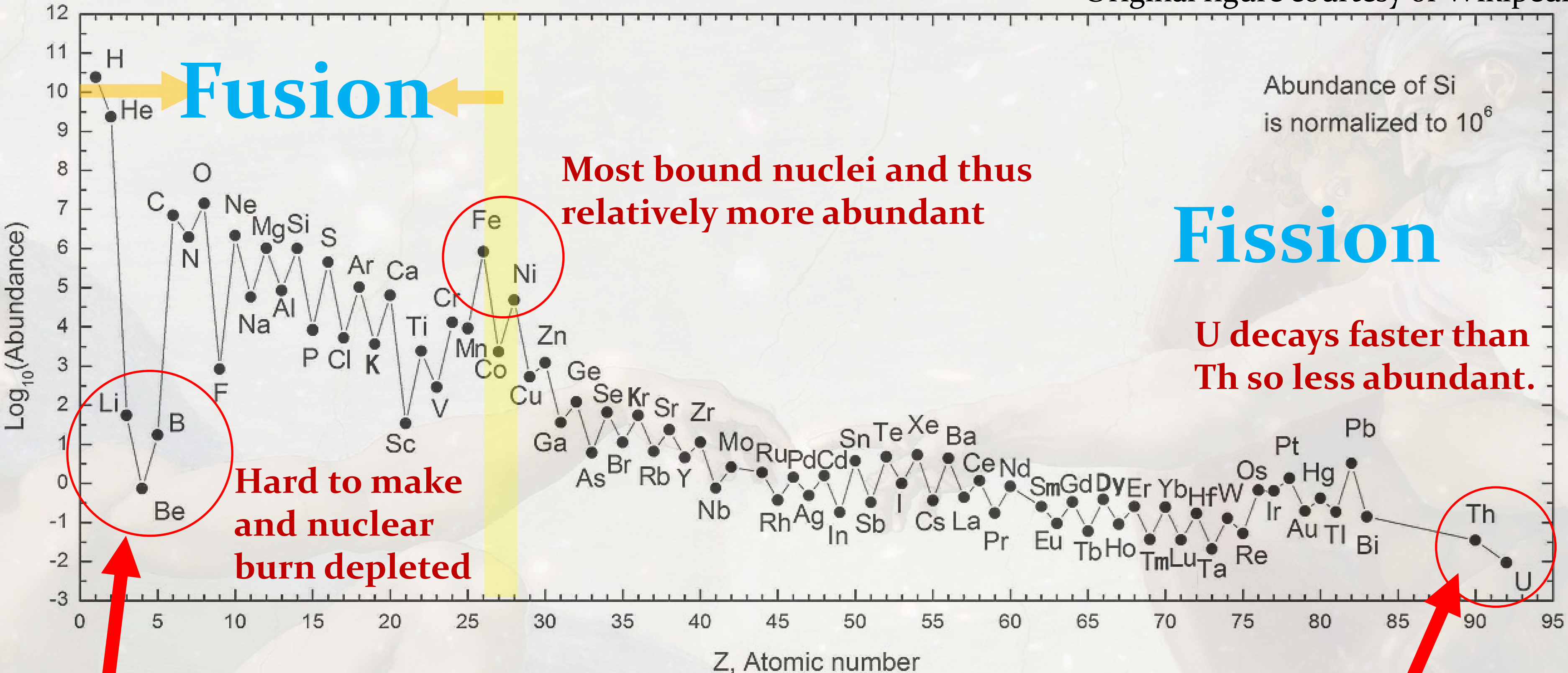


Graphic courtesy of Wikipedia

- This process is responsible for most of the energy production within the Sun as well as most low-mass stars.
- Every alpha produces releases about 14 MeV of energy from the binding energy per nucleon.
- The PP chain uses both the weak and strong interactions:
  - The weak interaction in the first step converts protons into deuterons.
  - The strong interaction then accomplishes the second and third steps to make intermediate helium-3 and finally the product helium-4.

The abundance of elements is the outcome of BBN and stellar nucleosynthesis

Original figure courtesy of Wikipedia



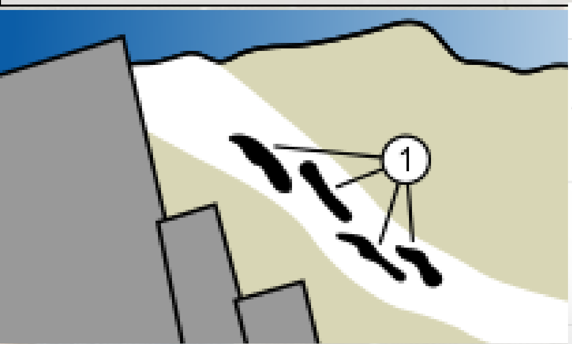
The light elements of lithium, boron and beryllium are suitable for aneutronic fusion.

Fuel for standard fission reactors

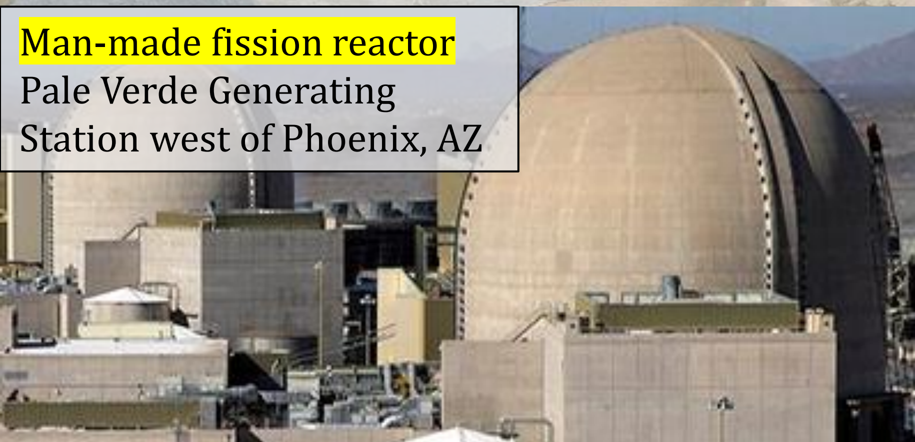
Fission versus fusion

Fission processes break apart large nuclei

Natural fission reactor
Present 2 billion years ago at Oklo, Gabon in Africa

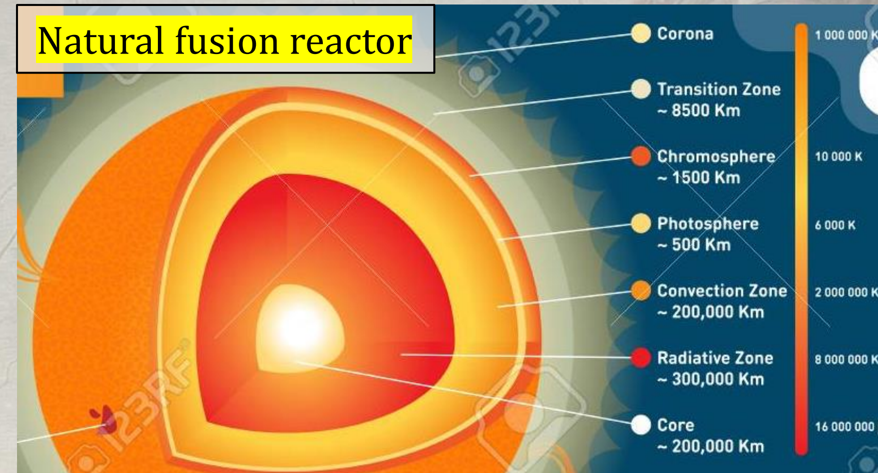


Man-made fission reactor
Pale Verde Generating Station west of Phoenix, AZ

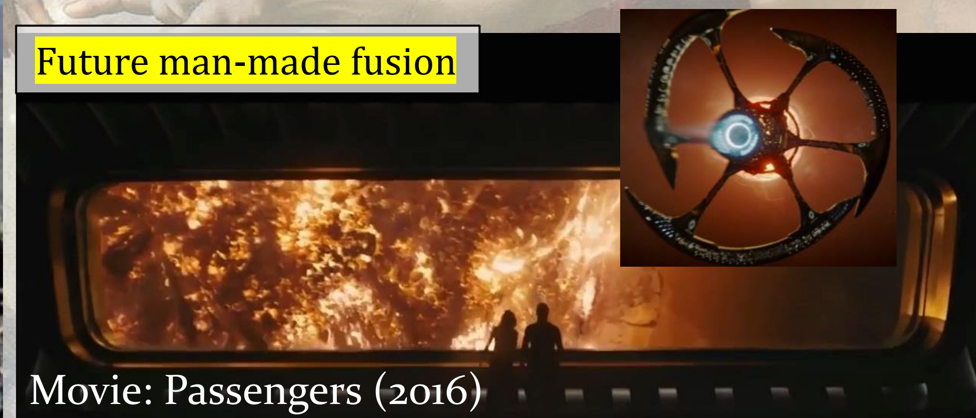


Fusion processes “fuse” or combine smaller nuclei into larger ones

Natural fusion reactor



Future man-made fusion



Movie: Passengers (2016)

Manmade fusion awakening

Dozens of government and commercial projects and companies are all chasing fusion.

iter

Oct. 2007

Laser Mégajoule LMJ

tae TECHNOLOGIES

HB11 ENERGY

NIF

Sandia National Laboratories Z

Marvel Fusion

$100 Billion ← $100 Million → $10 Million

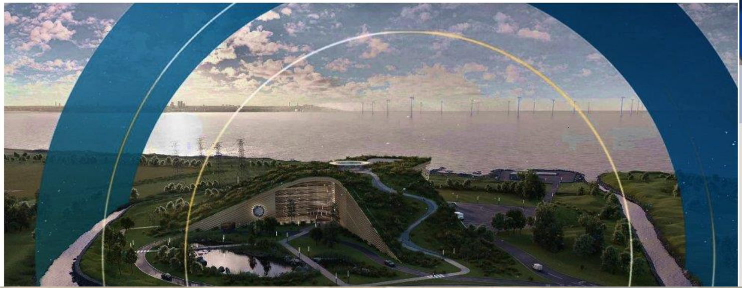
Nuclear pioneer First Light Fusion ignites plan for £400m fundraising

The Oxford-based nuclear fusion company is working with bankers at UBS to raise one of the biggest-ever funding rounds by a British energy start-up, Sky News learns.

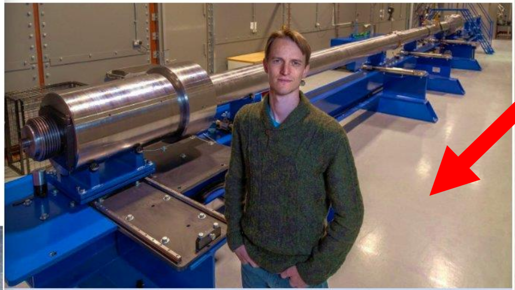
Mark Kleinman
City editor @MarkKleinmanSky

Tuesday 2 August 2022 12:28, UK

August 2022



Critical to this is the demonstration that its technology generates more energy than the amount expended in the process.



Dr Nick Hawker, chief executive of First Light Fusion with the UK's largest hyper-velocity gas gun

Kwasi Kwarteng, the business secretary, has said that the company's "British-born technology could potentially revolutionise power production in the coming decades".

First Light Fusion claims to have made more rapid progress towards its objectives than any other fusion technology in history.

Every month a new fusion startup pops up and asks for half a billion. The appetite is growing.

Governments are also recognizing modern fusion as a strategic investment opportunity.

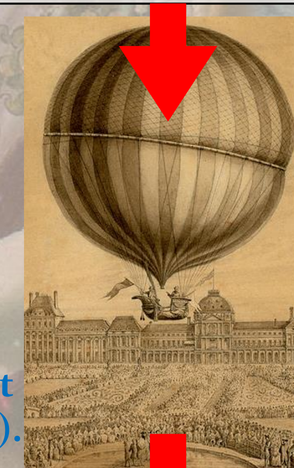
There are many different fusion reactors natural and (planned) manmade

Can we facilitate nuclear fusion via a different path as compared to early Universe Big Bang nucleosynthesis (BBN) or stellar core reactors?

What can we change?

We can change the type of nuclear fusion fuel used and method of confinement e.g. replacing gravity force with magnetic fields. Result: Development of deuterium-tritium fusion reactor for past 70 years.
This is like the evolution of the chariot (1,000s of years).

We can change the mechanism and process entirely by using lasers, plasmonics and light elements and their isotopes.
Transport without wheels (200 years).



ITER = International Thermonuclear Experimental Reactor

ITER is a $70 billion experiment: Start 2050?

CNN

Bottling the sun

The world has been trying to master this limitless clean energy source since the 1930s. We're now closer than ever

Story by Boštjan Videmšek
Photographs by Matjaž Krivic
May 30, 2022

ITER Divertor

ITER site in May 2021

scientific reports
www.nature.com/scientificreports

Potential design problems for ITER fusion device

A. Hassanein ✉ & V. Sizyuk

The ITER reactor design was simulated in full and exact 3D geometry including all known relevant physical processes involved during these transient events. The current ITER divertor design may not work properly and may requires significant modifications or new innovative design to prevent serious damage and to ensure successful operation.

Center for Materials Under Extreme Environment (CMUXE), Purdue University, West Lafayette, IN 47907, USA.
✉email: hassanein@purdue.edu

Scientific Reports | (2021) 11:2069 | https://doi.org/10.1038/s41598-021-81510-2 nature research

PHYSICS TODAY | MAY 2022

ISSUES & EVENTS

Further delays at ITER are certain, but their duration isn't clear

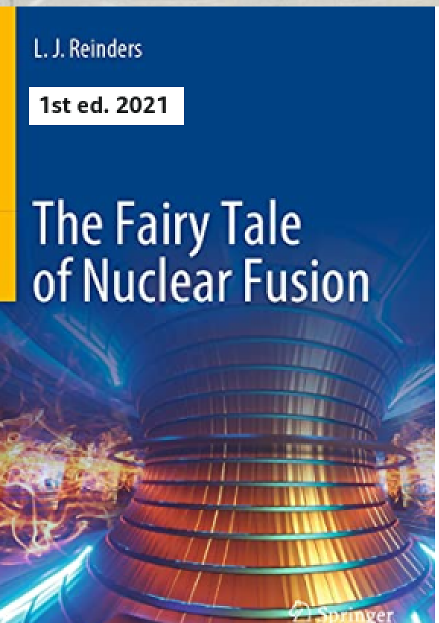
A halt to construction, pandemic-caused delays in deliveries, labor strife, and concerns about potential beryllium exposure are among recent challenges to the fusion project.

What others are saying about ITER

French Nobel laureate Pierre-Gilles de Gennes: “**The ITER project has been supported by Brussels for political image reasons and this is a mistake.**”

Another French Nobel laureate Georges Charpak: “**Let’s stop ITER, the useless and overpriced reactor.**”

Claessens, M. (2020). Those Who Are Against ITER. In: ITER: The Giant Fusion Reactor. Copernicus, Cham. https://doi.org/10.1007/978-3-030-27581-5_7



978-3030643430

ITER

The Fairy Tale of Nuclear Fusion

by L. J. Reinders (Author)

This carefully researched book presents facts and arguments showing, beyond a doubt, that nuclear fusion power will not be technically feasible in time to satisfy the world's urgent need for climate-neutral energy.

The author describes the 70-year history of nuclear fusion; the vain attempts to construct an energy-generating nuclear fusion power reactor, and shows that even in the most optimistic scenario nuclear fusion, in spite of the claims of its proponents, will not be able to make a sizable contribution to the energy mix in this century, whatever the outcome of ITER. This implies that fusion power will not be a factor in combating climate change, and that the race to save the climate with carbon-free energy will have been won or lost long before the first nuclear fusion power station comes on line.

Aimed at the general public as well as those whose decisions directly affect energy policy, this book will be a valuable resource for informing future debates.

978-3030747336

... unlike other areas of physics, investigations of fusion reactors became politicized relatively early. In the 1960s, independent research labs themselves decided what fusion research problems to pursue. But in the 1970s, the Atomic Energy Commission steered the fusion community away from fundamental research and toward the creation of commercial energy from fusion. It was just too soon to think about commercializing fusion because numerous fundamental issues in plasma physics had yet to be resolved. And in fact, that’s still the case today...

Journal of Fusion Energy (2019) 38:315–329
https://doi.org/10.1007/s10894-018-0182-1

ORIGINAL RESEARCH

CrossMark

Fusion Neutrons: Tritium Breeding and Impact on Wall Materials and Components of Diagnostic Systems

Marek Rubel[1]

Published online: 1 September 2018

Unsolved dt-fusion problems

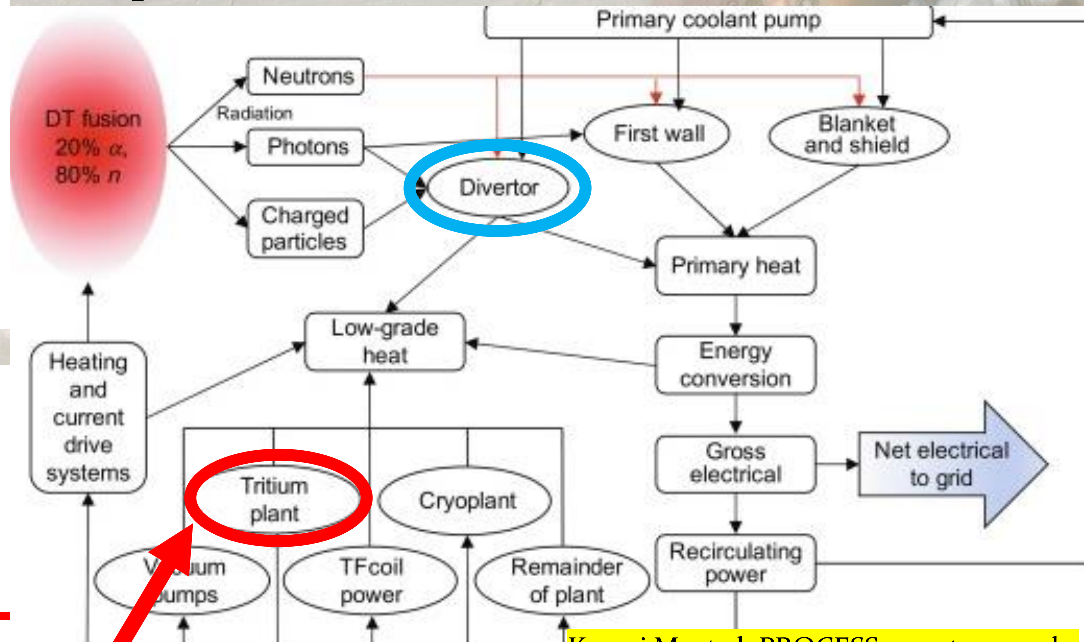
The success or failure of dt based nuclear fusion resides in the reactor's ability to safely absorb the hard neutron radiation and self-produce its own fuel tritium.

Fast neutrons are to deposit their energy in the absorber (reactor blanket) to facilitate heat exchange and transfer to electricity generating systems of a power plant and, simultaneously, for tritium production via nuclear reactions in the blanket.

The best way to exemplify the general power balance into consider a reactor of, for instance, 500 MW of fusion power. 80% of that (i.e. 400 MW) will be associated with neutrons and the rest (100 MW) with alphas. To the latter

• • •

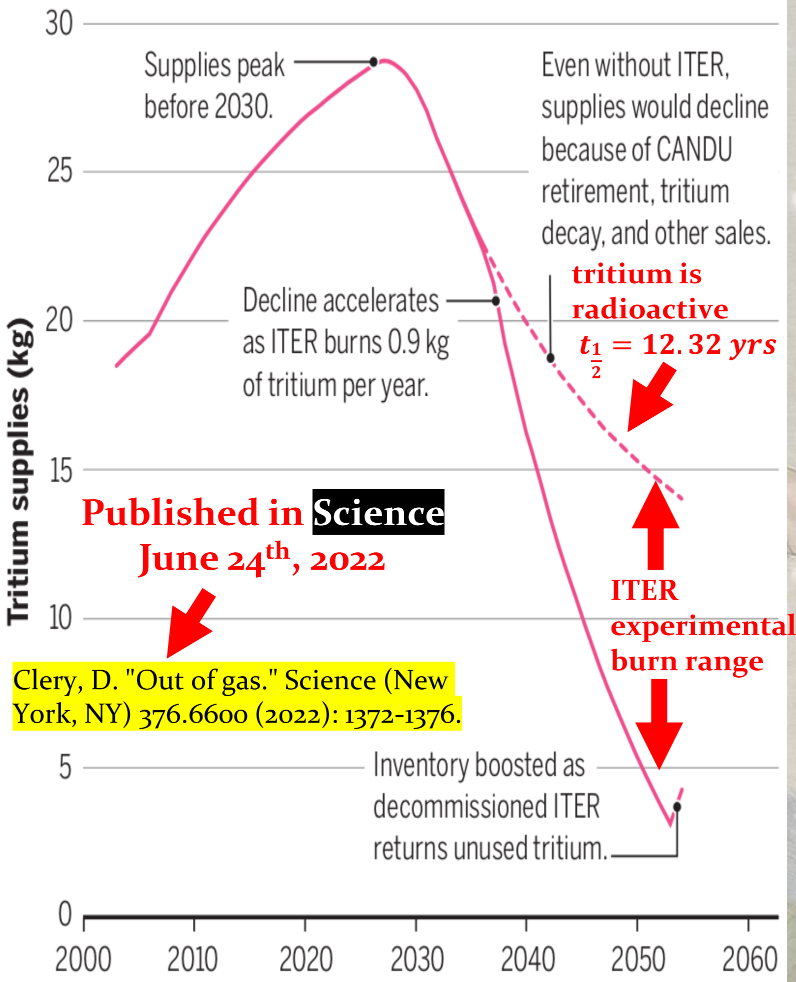
steady–steady reactor operation. The entire dream and all hopes for commercial exploitation of controlled thermonuclear fusion for energy production depend on all aspects of power handling by PFC, efficient extraction of neutron energy and on efficient production, extraction and handling of tritium to fuel the reactor. In summary, it will depend on neutrons.



Kovari M, et al. PROCESS: a systems code for fusion power plants—part 2: engineering, Fusion Eng Des 2016; 104:9–20.

Where are we going to get all the tritium? (slide to follow)

The few kilograms of commercially available tritium come from CANDU plants, a type of nuclear reactor in Canada and South Korea. According to ITER projections, supplies will peak this decade, then begin a steady decline that will accelerate when ITER begins burning tritium.



"Out of gas" (tritium)

One 1 GW electrical power reactor needs to produce about 2.8 GW of thermal power and burns 160 kg of tritium per year.

Is there enough tritium fuel to run just one reactor?

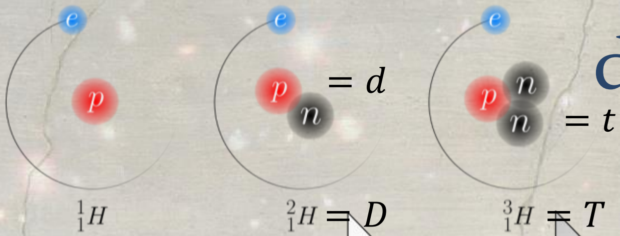
A dt-cycle fusion plant must produce tritium from the high flux of neutrons. The dt-fusion economy would need to be grown slowly into many reactors which is at risk from fuel disruption because of the natural decay of tritium.

Breeding a large excess amount of tritium required in growing the dt-fusion economy is an unsolved problem.

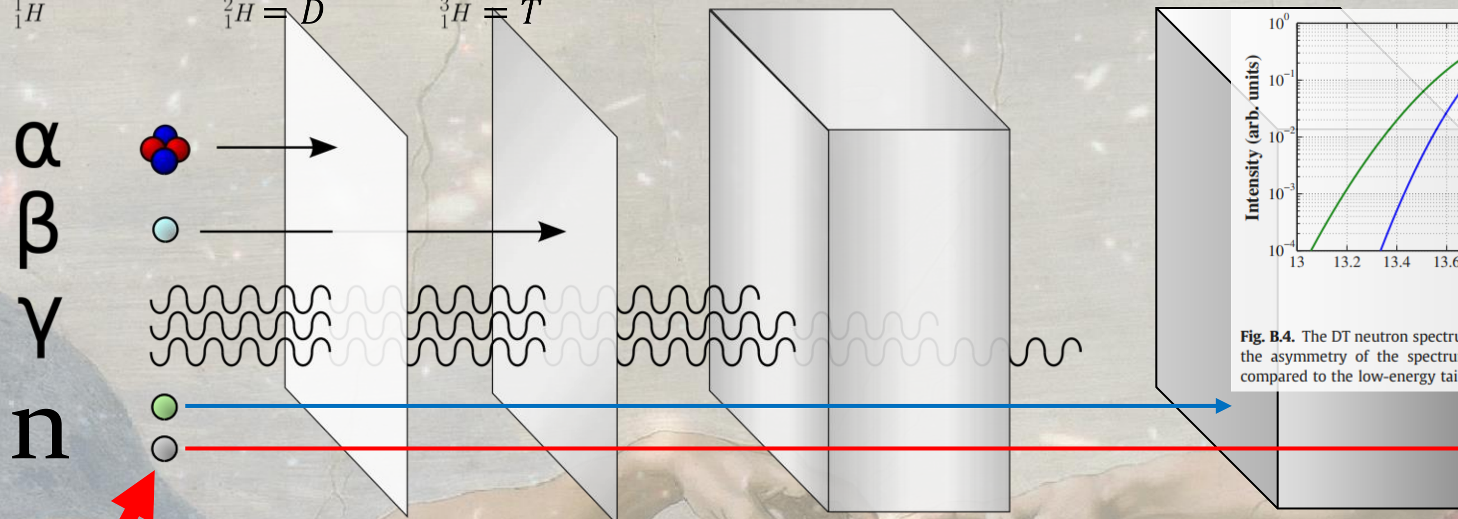
Conclusion: The dt-fusion economy, if technologically realizable, is well beyond a 100-year horizon. With technological advances in aneutronic fusion, the chance that the dt-fusion economy will be relevant is negligible.

One experimental reactor burns it all

dt-fusion **safety** and **radioactive** waste



Appelbe, B., and J. Chittenden. "Relativistically correct DD and DT neutron spectra." High Energy Density Physics 11 (2014): 30-35.



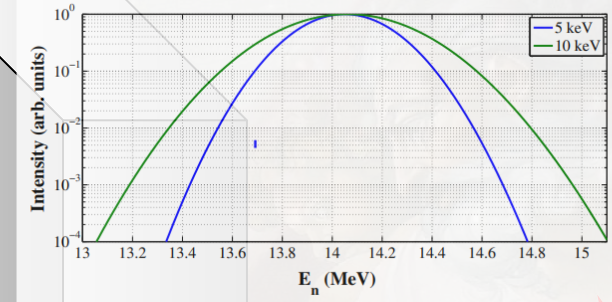


Fig. B.4. The DT neutron spectrum for ion temperatures of 5 keV and 10 keV showing the asymmetry of the spectrum with a greater intensity in the high-energy tail compared to the low-energy tail of the spectrum.

14 MeV neutrons
(dt process)
$v_n = 0.173c$

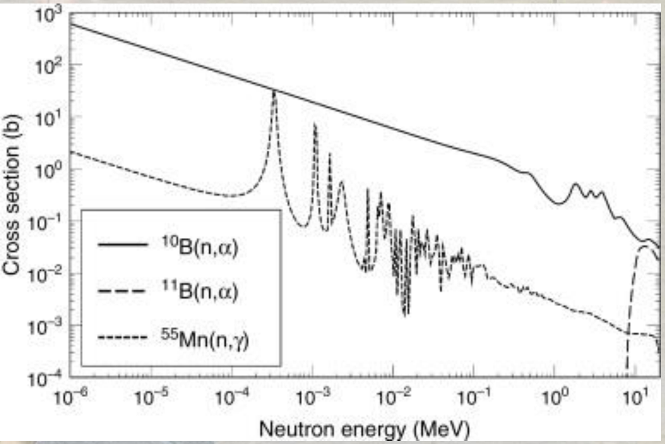
$$m_n c^2 = 940\ \text{MeV}$$

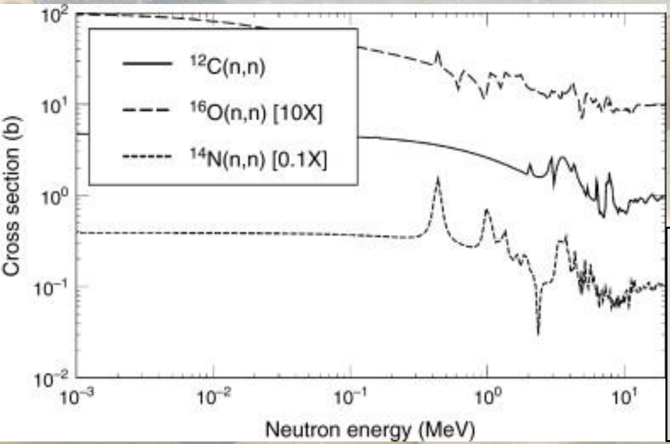
$$d + t \rightarrow \alpha(3.6\ \text{MeV}) + n(14\ \text{MeV})$$

dt-fusion leads to super-fast neutrons and associated problems: My objective today is the development of aneutronic fusion in a dynamic regime i.e. non-thermal equilibrium, forbidden by brems-losses.

MeV energy units: M = million and eV is the kinetic energy a unit charged particle acquires in a 1 Volt step

The trouble with dt-fusion 14 MeV neutrons





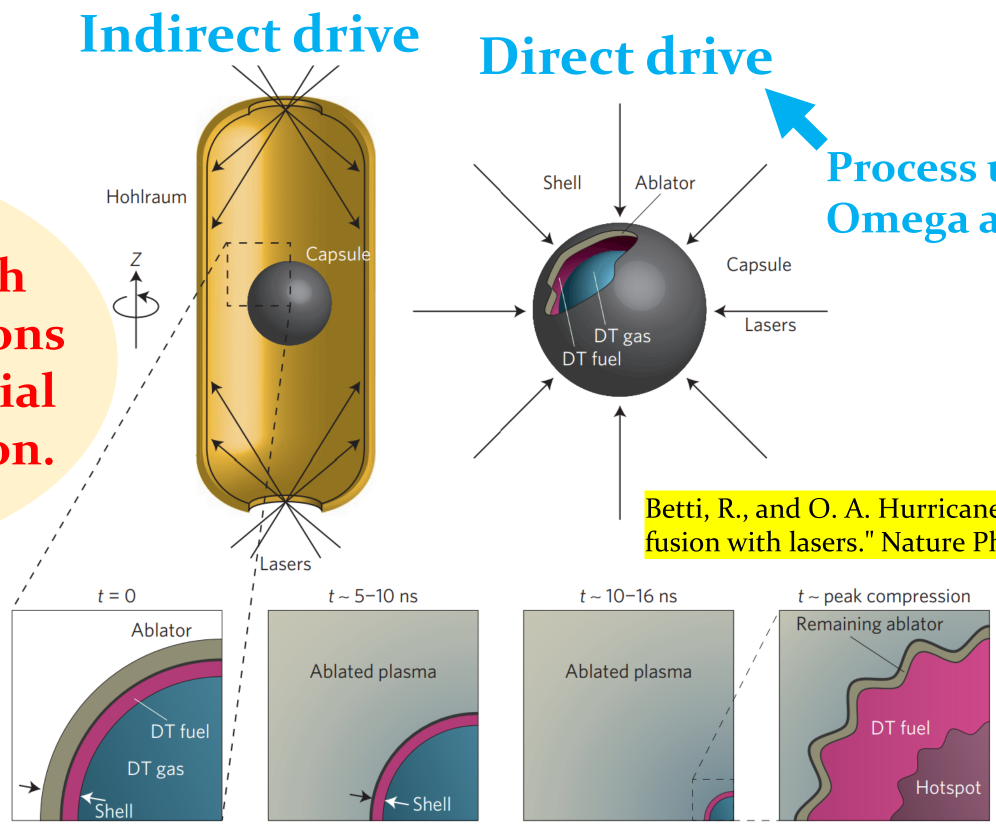
The collision cross-section of 14 MeV neutrons in matter is typically 10 times (or more!) smaller compared to MeV neutrons. Therefore, the neutron energy declines slowly from collisions (moderation). Containment walls must then be very thick. Much of the material is subject to element transmutation from exposure to such high energy and high intensity dt fusion neutrons.

Since 80% of fusion energy is released in the form of 14 MeV neutrons, the containment vessel is both the source of energy to drive the turbines and the source of tritium needed for fusion from element transmutation.

In aneutronic systems (e.g. pB), occasional neutrons carry a fraction of a percent of the total energy and material for fusion can be mined.

Inertial confinement fusion

REVIEW ARTICLES | INSIGHT
NATURE PHYSICS DOI: 10.1038/NPHYS3736



Reminder: All problems with tritium and neutrons also apply to inertial confinement fusion.

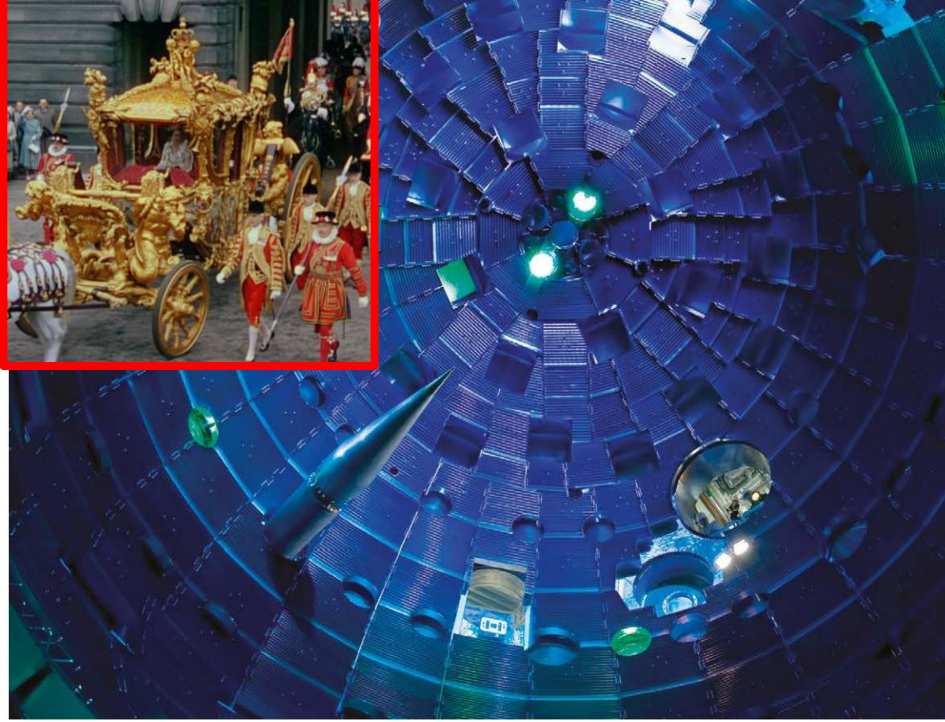
Originally envisioned with heavy-ions, but ultimately developed using laser pulses.

Betti, R., and O. A. Hurricane. "Inertial-confinement fusion with lasers." Nature Physics 12.5 (2016): 435-448.

Figure 1 | Schematics of indirect- and direct-drive ICF. Typical targets used in laser-driven ICF are indirectly driven (upper left) or directly driven (upper right). In either case, a spherical capsule is prepared at $t = 0$ with a layer of DT fuel on its inside surface. As the capsule surface absorbs energy and ablates, pressure accelerates the shell of remaining ablator and DT fuel inwards—an implosion. By the time the shell is at approximately one-fifth of its initial radius it is travelling at a speed of many hundreds of kilometres per second. By the time the implosion reaches minimum radius, a hotspot of DT has formed, surrounded by colder and denser DT fuel.

Problems with intertial fusion

Personal point of view: Direct drive inertial confinement laser fusion unsuitable for any meaningful power generation. It is useful for a femto-version of an H-bomb. This is also where the funding of NIF came from.



Inside the target chamber at the US National Ignition Facility.

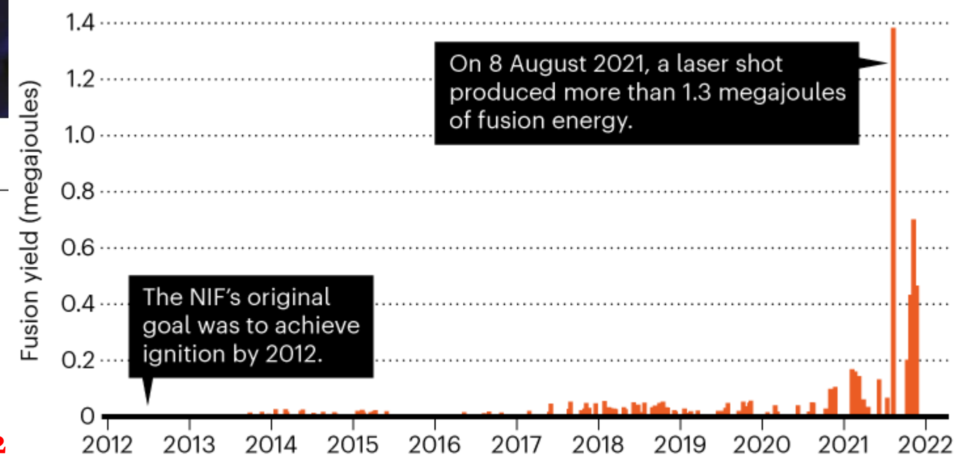
LASER-FUSION FACILITY HEADS BACK TO THE DRAWING BOARD

Published July 22nd, 2022

US scientists evaluate their options after failing to replicate record-setting experiment from 2021.

THE ROAD TO IGNITION

The National Ignition Facility (NIF) struggled for years before achieving a high-yield fusion reaction (considered ignition, by some measures) in 2021. Repeat experiments, however, produced less than half the energy of that result.



Tollefson, Jeff. "Exclusive: Laser-fusion facility heads back to the drawing board." Nature 608.7921 (2022): 20-21.

The tantalizing fusion promise is marred by hidden pitfalls

The most famous example of a pitfall is the "cold fusion" of 1989 which has been currently rebranded as "Low-Energy Nuclear Reactions" or LENR.
Perfect topic for TV shows (Dr. Who) and movies (The Saint) which I enjoy. Airbus and Google should take note.

Airbus Files Patent for LENR 'Power-Generating Device'

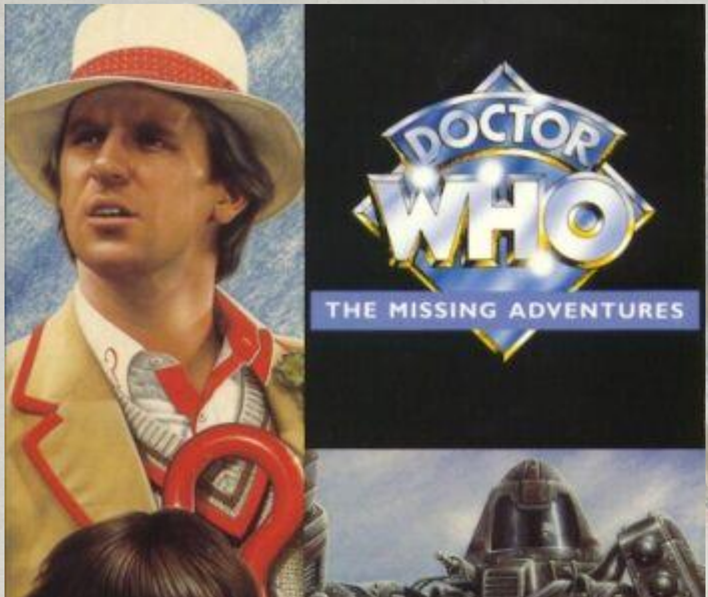
Posted on March 22, 2015 • 102 Comments

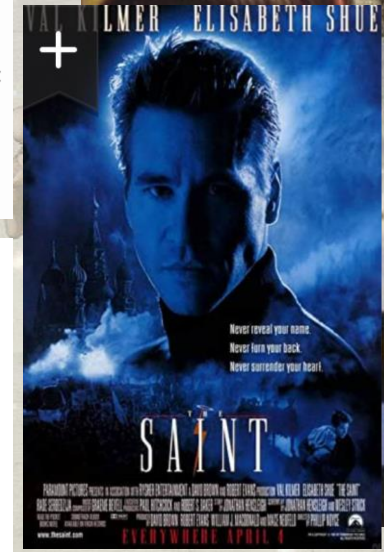
Thanks to AlainCo for posting about a recently published patent application submitted by European Aerospace giant Airbus for an 'apparatus and method for power generation'. It appears that patent was first submitted on September 17, 2013, and was made public on March 19th, 2015. So it seems that Airbus has been paying attention for quite some time now, perhaps they were inspired by the publication of the E-Cat report by Levi et al which was published in May 2013.

NEWS | 27 May 2019 | Clarification 28 May 2019

Google revives controversial cold-fusion experiments

Researchers tested mechanisms linked to nuclear fusion at room temperature – but found no evidence for the phenomenon.





Tabletop approaches A: Muon-catalyzed fusion

J.D. Jackson reminisces in 2010: "**Luis Alvarez** and colleagues discovered muon-catalyzed fusion of hydrogen isotopes by chance in late 1956. On sabbatical leave at Princeton University during that year, I read the first public announcement of the discovery at the end of December in that well-known scientific journal, The New York Times. A nuclear theorist by prior training, I was intrigued enough in the phenomenon to begin some calculations."

Jackson, J.D. A Personal Adventure in Muon-Catalyzed Fusion. Phys. Perspect. 12, 74–88 (2010). https://doi.org/10.1007/s00016-009-0006-9

an Article from SCIENTIFIC AMERICAN JULY, 1987 VOL. 255 NO. 7

μ- Cold Nuclear Fusion

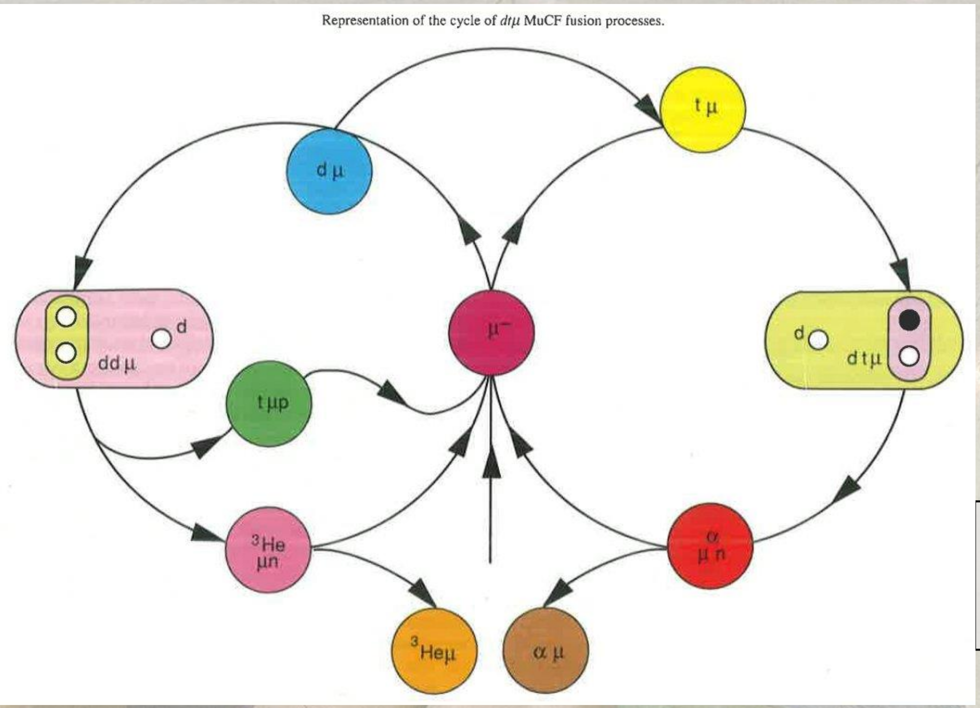
The electronlike particles called muons can catalyze nuclear fusion reactions, eliminating the need for powerful lasers or high-temperature plasmas. The process may one day become a commercial energy source

by Johann Rafelski and Steven E. Jones

Modern nuclear fusion processes occur under inequilibrium conditions with the objective to spark a nano-fusion explosion which is short lived.

Muon-catalyzed fusion (μCF) cycle

The muon is the catalyzer for dt-fusion allowing a single muon to facilitate many fusion events.



- The muon is a heavy electron with 207 times more mass therefore muonic atoms are shrunk by a factor of 207.
- Muonic molecules of hydrogen are then also shrunk which allows rapid spontaneous fusion at any temperature and pressure.
- For $dt\mu^+$ molecules, the fusion rate is a million times faster than the natural decay of the muon.
- The greatest challenge to μCF is the loss of the muon due to binding with the produced alpha particles. This limits the number of observed fusions to about 200 per muon.

The physics breakeven point for $dt\mu$ cycle was achieved around 1988.

B: Laser driven aneutronic proton-boron fusion

Belyaev, V.S.; et al. (2005). "Observation of neutronless fusion reactions in picosecond laser plasmas". Physical Review E. 72 (2): 026406. doi:10.1103/physreve.72.026406

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Published online: 26 August 2005; | doi:10.1038/news050822-10

Lasers trigger cleaner fusion

Neutron-free reaction makes less radioactive waste.

Mark Peplow

Two-laser process

Aneutronic fusion reactions require a spark of protons in the 0.01-1 MeV energy range

Patent Production of energy via laser-initiated aneutronic nuclear fusion reactions

Abstract

The invention relates to the production of energy with laser beams, involving: a) exciting a fuel target (4) into a plasma state using a first set of laser beams (1); b) bombarding the fuel target in the plasma state with particles generated using a second set of laser beams (2), the fuel and the particles being chosen so that the interaction between the fuel target in the plasma state and the particles produce non-thermal equilibrium aneutronic nuclear reactions; and c) recovering energy from the ions generated by the aneutronic nuclear reactions.

WO2013144482A1
WIPO (PCT)

2013-10-03 • Publication of WO2013144482A1

Other languages: French

Application PCT/FR2013/050558
2012-03-27 • Priority to FR1252750A
Inventor: Christine LABAUNE, Johann Rafelski, Sylvie DEPIERREUX, Clément GOYON, Vincent YAHIA

A mJ femtosecond laser is capable of producing reactant protons for fusion

For any aneutronic fusion process, cheap and abundant MeV scale protons are essential.

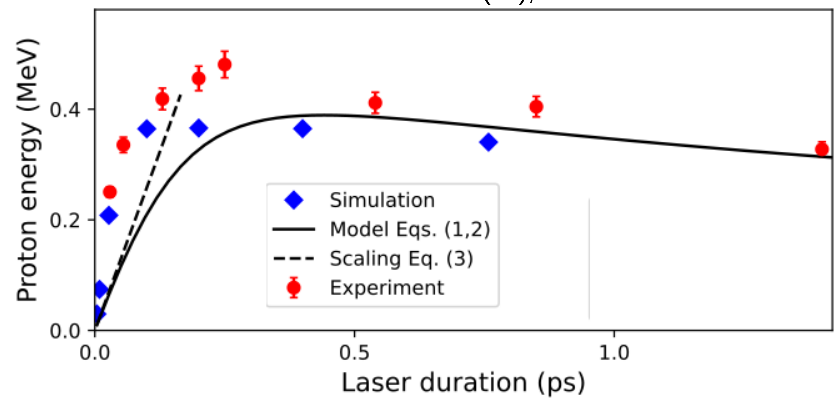
Low-divergence MeV-class proton beams from kHz-driven laser-solid interactions

Dan Levy,[1,*] Igor A. Andriyash,[2,†] Stefan Haessler,[2,‡] Jaismeen Kaur,[2] Marie Ouillé,[2,3] Alessandro Flacco,[2] Eyal Kroupp,[1] Victor Malka,[1] and Rodrigo Lopez-Martens[2]

[1]*Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel*
[2]*Laboratoire d'Optique Appliquée, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 828 Bd des Maréchaux, 91762 Palaiseau, France*
[3]*Ardop Engineering, Cité de la Photonique, 11 Avenue de la Canteranne, Bât. Pléione, 33600 Pessac, France*

Proton beams with up to 100 pC bunch charge, 0.48 MeV cut-off energy and divergence as low as a 3° were generated from solid targets at kHz repetition rate by a few-mJ femtosecond laser under controlled plasma conditions. The beam spatial profile was measured using a small aperture scanning time-of-flight detector. Detailed parametric studies were performed by varying the surface plasma scale length from 8 to 80 nm and the laser pulse duration from 4 fs to 1.5 ps. Numerical simulations are in good agreement with observations and, together with an in-depth theoretical analysis of the acceleration mechanism, indicate that high repetition rate femtosecond laser technology could be used to produce few-MeV protons beams for applications.

arXiv:2112.12581 16 Dec 2021 (v1), last revised 12 Jul 2022



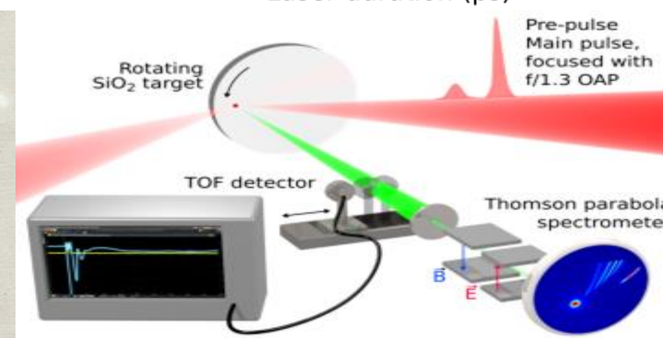
scientific reports
www.nature.com/scientificreports

June 13th, 2022

Low divergent MeV-class proton beam with micrometer source size driven by a few-cycle laser pulse

Prashant K. Singh[1✉], Parvin Varmazyar[1], Bence Nagy[1], Joon-Gon Son[1,2], Sargis Ter-Avetisyan[1] & Karoly Osvay[1,3✉]

Spatial characterization of 0.5 MeV proton beam, driven by 12 fs, 35 mJ, 10^{19} W/cm² intense laser-foil interaction is presented. The accelerated proton beam has been applied to obtain a high-resolution, point-projection static radiograph of a fine mesh using a CR-39 plate. The reconstruction of mesh edge blurring and particle ray tracing suggests that these protons have an effective source size (FWHM) of just 3.3 ± 0.3 µm. Furthermore, the spatial distribution of the proton beam recorded on the CR-39 showed that the divergence of these particles is less than 5-degree (FWHM). The low divergence and small source size of the proton beam resulted in an ultralow transverse emittance of 0.00032 π-mm-mrad, which is several orders of magnitude smaller than that of a conventional accelerator beam.



Two-laser pB process

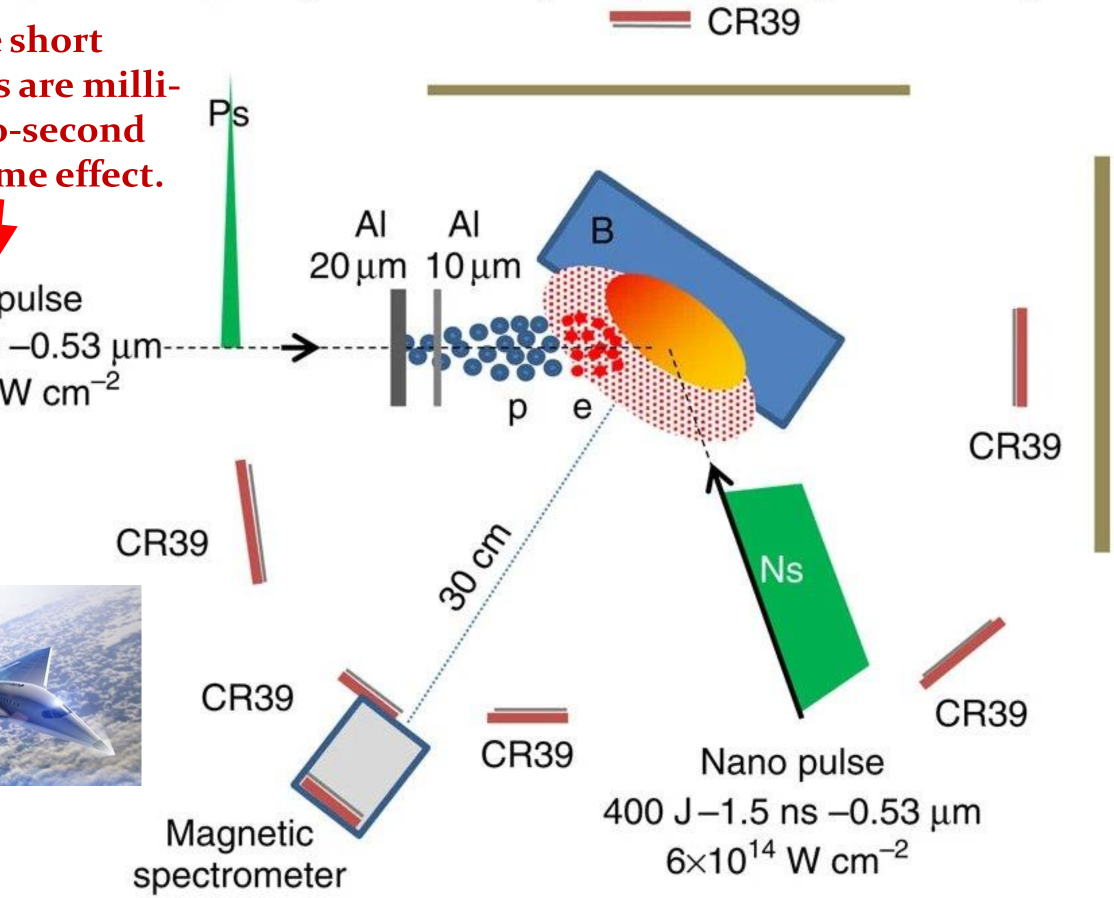
The long-pulsed nano-laser produces plasma and sweeps electrons away.

The short-pulsed pico-laser produces a beam of reactant protons. Fusion reactions occur prior to protons reaching thermal equilibrium.

Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

Scheme of the experimental set-up showing the laser beam configuration, the target arrangement and the diagnostics

Alternative short pulse lasers are milli-Joule femto-second level for same effect.



nature COMMUNICATIONS

ARTICLE

Received 24 Jan 2013 | Accepted 27 Aug 2013 | Published 8 Oct 2013 DOI: 10.1038/ncomms3506

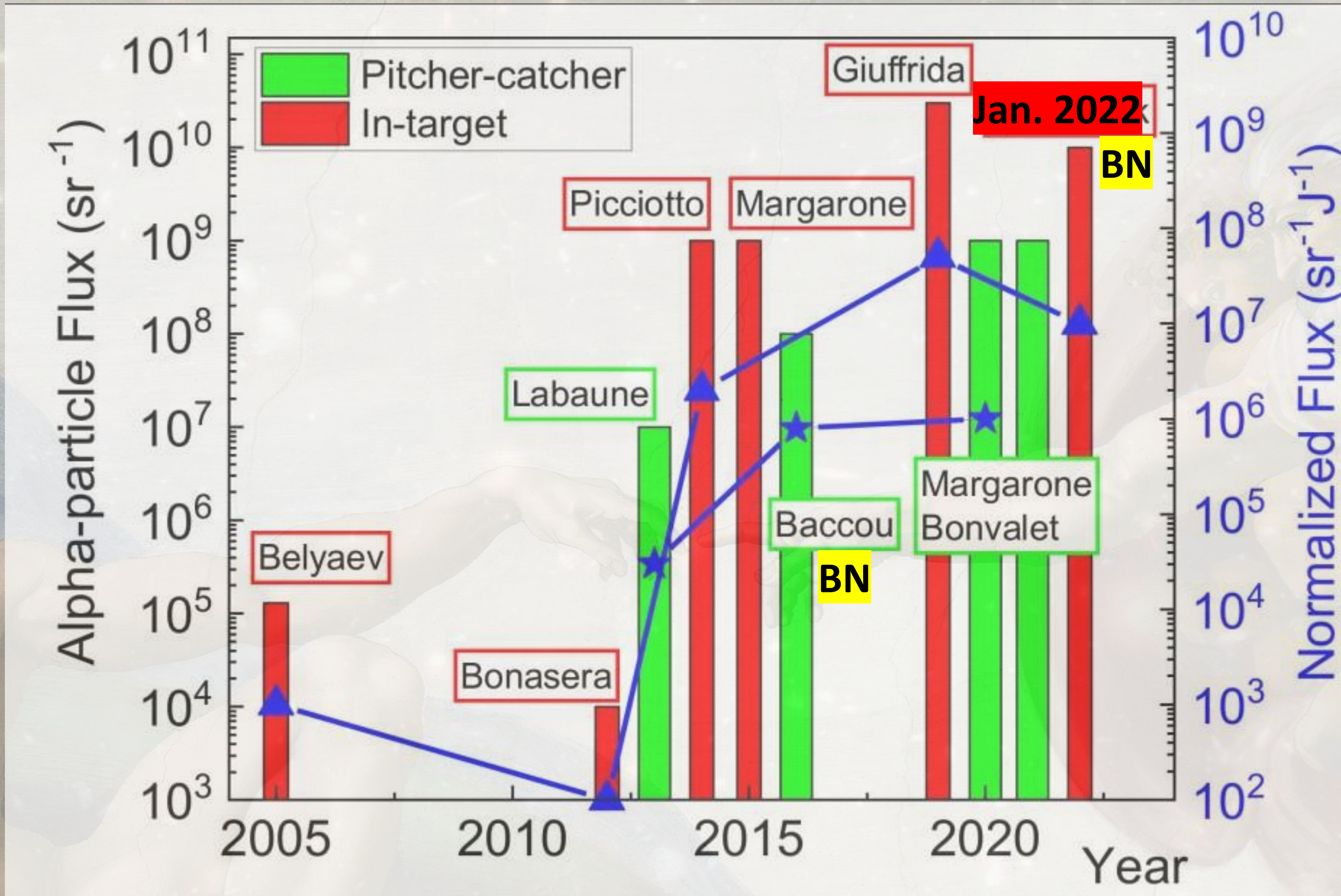
Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

C. Labaune[1], C. Baccou[1], S. Depierreux[2], C. Goyon[2], G. Loisel[1], V. Yahia[1] & J. Rafelski[3]

Laser Contrast Ratio: $R = \frac{Pulse\ Intensity}{Prepulse/pedestal\ Intenity}$

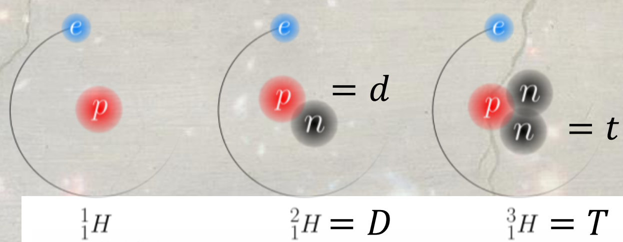
The laser contrast ratio is a crucial parameter in achieving laser-driven nuclear fusion.

The experimental progress in pB fusion measured in terms of α production

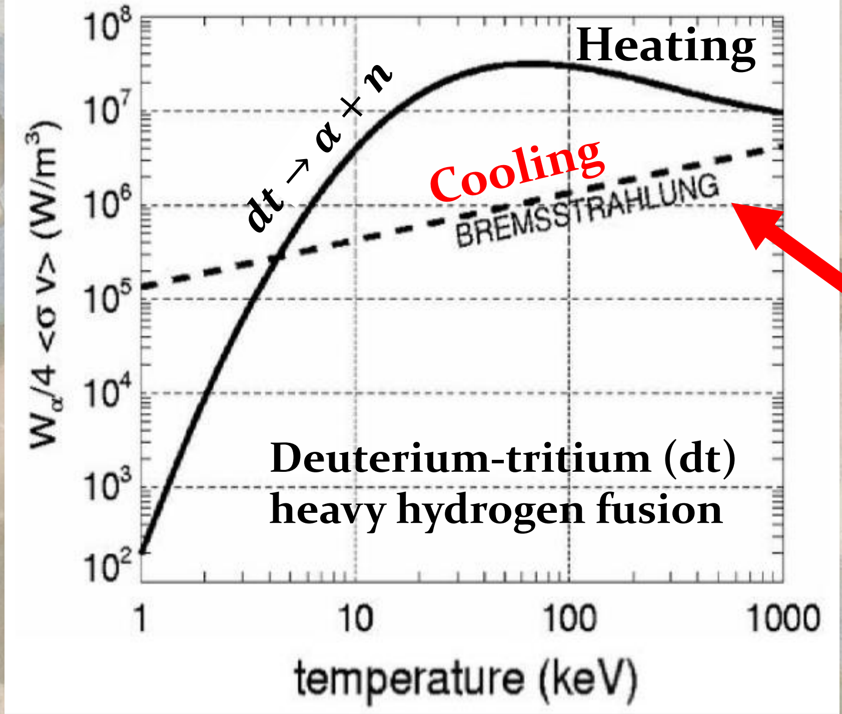


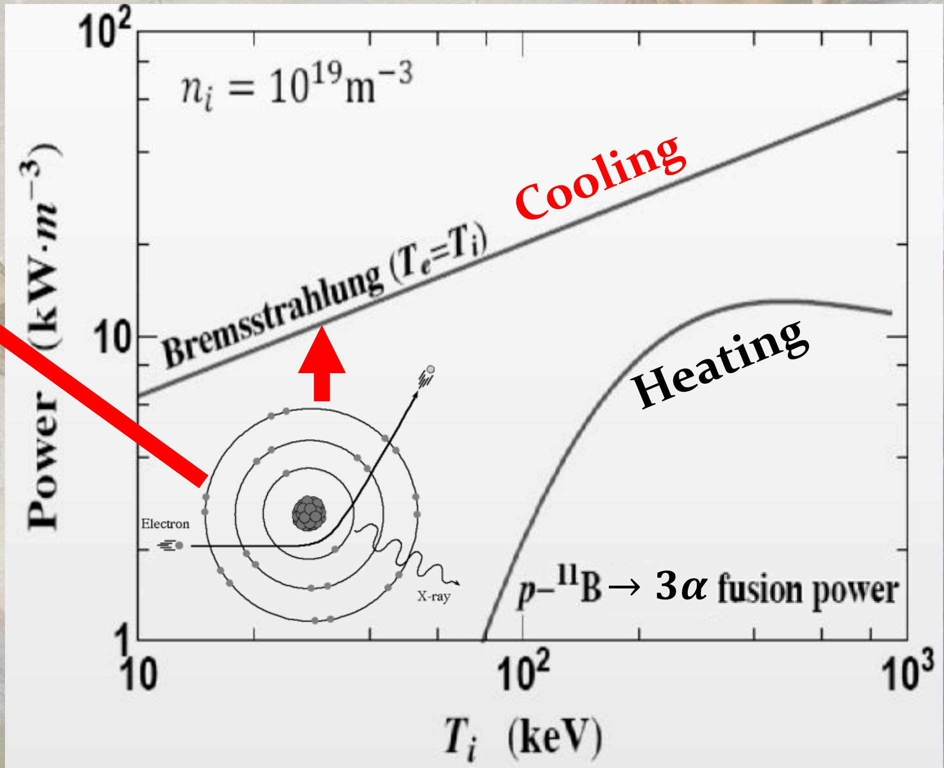
Why can‘t we burn pB in a thermal reactor?

Comparing neutronic and aneutronic fusion



Some advanced fuels (such as boron) do not allow steady state thermal fusion because of fusion output versus radiation loss.





C: Plasmonic fusion

Antennas for light

Lukas Novotny[1*] and Niek van Hulst[2,3]

nature photonics | REVIEW ARTICLE
PUBLISHED ONLINE: 1 FEBRUARY 2011 | DOI: 10.1038/NPHOTON.2010.237

Optical antennas are devices that convert freely propagating optical radiation into localized energy, and vice versa. They enable the control and manipulation of optical fields at the nanometre scale, and hold promise for enhancing the performance and efficiency of photodetection, light emission and sensing. Although many of the properties and parameters of optical antennas are similar to their radiowave and microwave counterparts, they have important differences resulting from their small size and the resonant properties of metal nanostructures. This Review summarizes the physical properties of optical antennas, provides a summary of some of the most important recent developments in the field, discusses the potential applications and identifies the future challenges and opportunities.

IOP Publishing | Royal Swedish Academy of Sciences — Physica Scripta
Phys. Scr. **91** (2016) 053010 (13pp) — doi:10.1088/0031-8949/91/5/053010
Invited Comment
Published 22 April 2016

Surface plasmons: a strong alliance of electrons and light

Norbert Kroó[1,3], Sándor Varró[1,2], Péter Rácz[1] and Péter Dombi[1,2]

[1] Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Institute for Solid State Physics and Optics, H-1525 Budapest, Pf. 49, Hungary [2] ELI-ALPS, H-6720 Szeged, Dugonics tér 13, Hungary

Surface plasmon polaritons (SPPs) have several unique properties, including their strong-field enhancing effect in near field. This means, among other things, that nonlinear phenomena may be studied at much lower laser intensities. The present paper describes in detail the theory of basic properties of SPPs, and our model of a laser-induced oscillating double-layer potential. The SPPs may decay into photons and hot electrons. The latter may be emitted by a multi-plasmon process. Experiments on both photon and electron emission from a gold film are briefly

PRX ENERGY

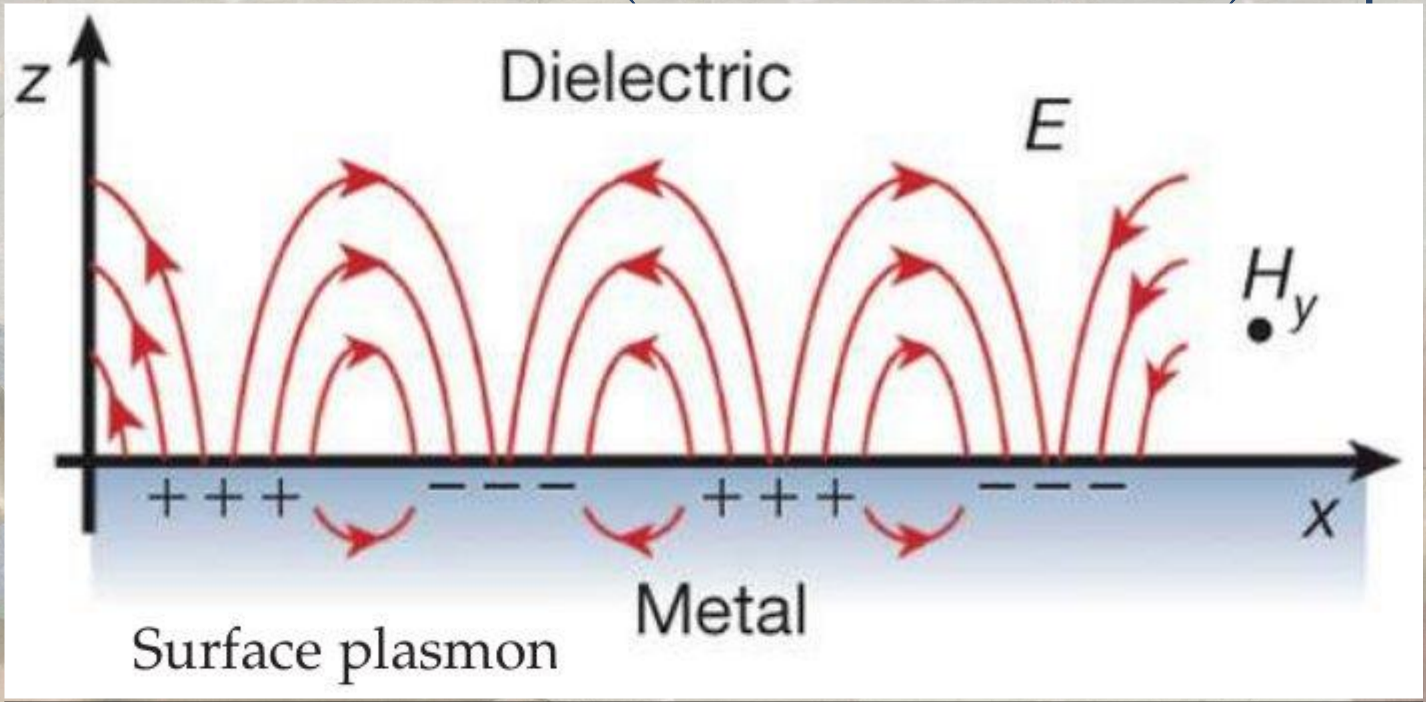
Kinetic Model Evaluation of the Resilience of Plasmonic Nanoantennas for Laser-Induced Fusion

István Papp, Larissa Bravina, Mária Csete, Archana Kumari, Igor N. Mishustin, Dénes Molnár, Anton Motornenko, Péter Rácz, Leonid M. Satarov, Horst Stöcker, Daniel D. Strottman, András Szenes, Dávid Vass, Tamás S. Biró, László P. Csernai, and Norbert Kroó (NAPLIFE Collaboration)

PRX Energy **1**, 023001 – Published 7 July 2022

Recently, a new version of laser-induced fusion was proposed where implanted nanoantennas regulated and amplified the light absorption in the fusion target [L.P. Csernai *et al.*, Phys. Wave Phenom. 28, 187–99 (2020)]. In this paper we estimate the nanoantenna lifetime in a dynamical kinetic model and describe how electrons are leaving the nanoantenna's surface, and for how long the plasmonic effect is maintained. Our model successfully shows a nanorod antenna lifetime that will allow future fusion studies with top-energy short laser ignition pulses.

Antenna response: Surface electro-magnetic fields 1000-fold (in numerical model) amplified



Nanoparticles act as resonant antennas working at a fraction of the incident light‘s wavelength.

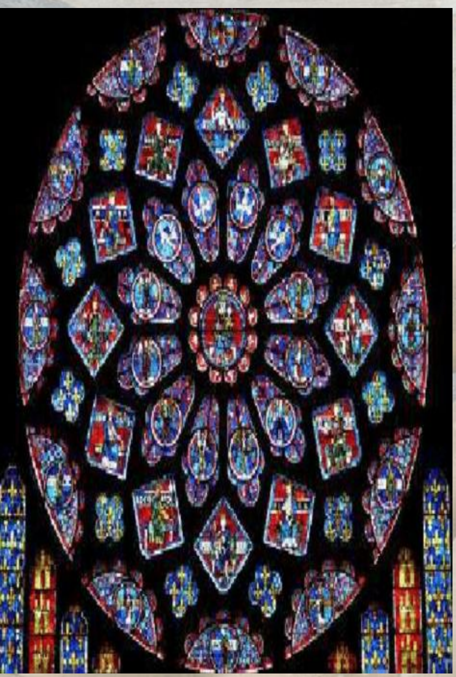
Resonance wavelength is determined by the electron density and geometry of the antenna.

Plasmon coherent dynamics lifespan requires sub-picosecond laser pulses.

Commercially available femto-sec mJ lasers can excite surface plasmons in dielectrics which can accelerate protons to MeV energies.

Antennas for light invented in ancient Imperial Rome

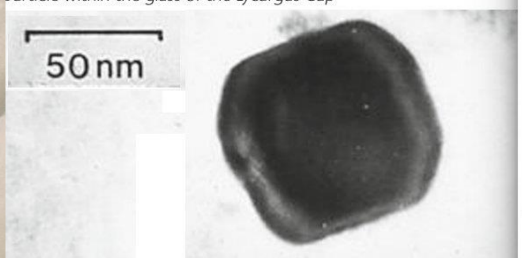
A nano-sized piece of metal can be viewed as a box trapping free electron plasma. The domain of physics describing how light interacts with metallic nano-structures embedded in an insulator is called **plasmonics.** Extreme daily light absorption properties of metallic nano particles have been empirically recognized and used in **medieval stained glass** (see e.g. The Grande Rose of the Chartres Cathedral); and in precious objects made of glass during the **Roman era (e.g. Lycurgus drinking cup).**

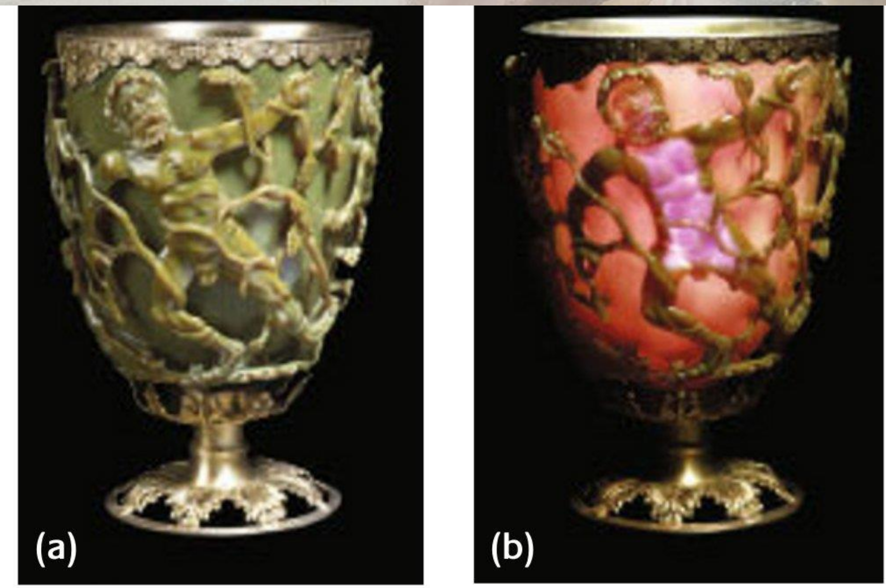


The Lycurgus Cup – A Roman Nanotechnology

Ian Freestone[1], Nigel Meeks[2], Margaret Sax[2] and Catherine Higgitt[2]

Transmission electron microscopy (TEM) image of a silver-gold alloy particle within the glass of the Lycurgus Cup

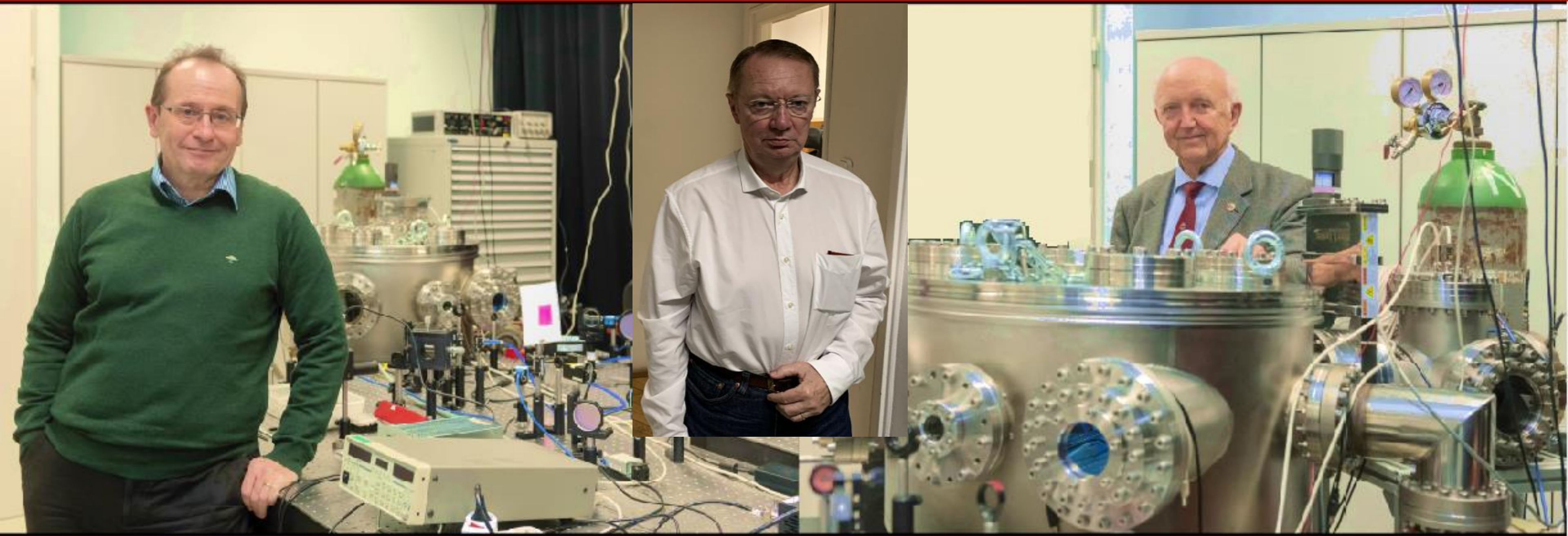




The Lycurgus Cup *1958,1202.1 in reflected (a) and transmitted (b) light. Scene showing Lycurgus being enmeshed by Ambrosia*

The NAPlife plasmonic fusion project

Tamás Biró László Pál Csernai Norbert Kroó



NAPlife Collaboration:

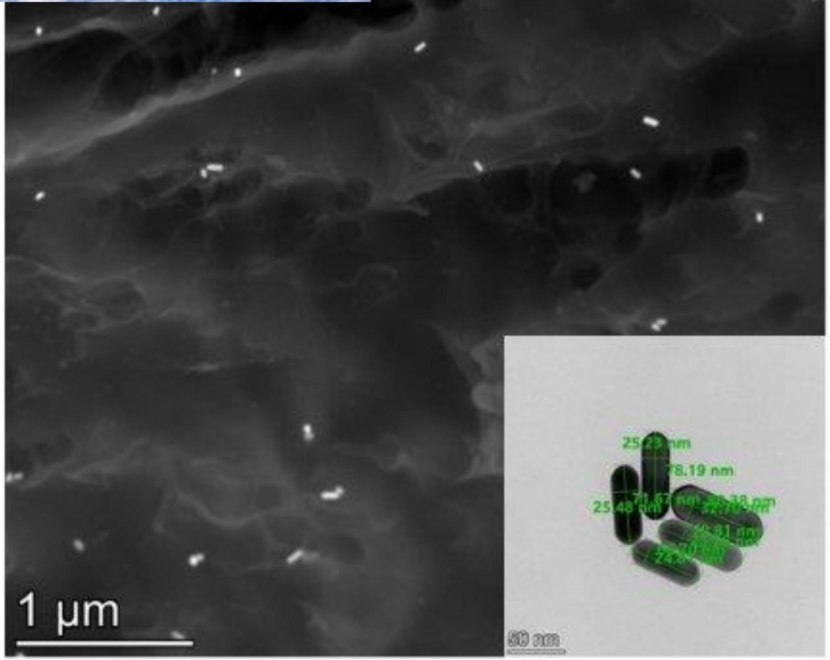
Márk Aladi, Tamás S Biró, Attila Bonyár, Alexandra Borók, László P Csernai, Mária Csete, Attila Czirják, Péter Dombi, Olivér Fekete, Péter Földi, Gábor Galbács, Román Holomb, Csaba Horváth, Judit Kámán, Miklós Kedves, Norbert Kroó, Archana Kumari, Ágnes N Szokol, István Papp, Péter Petrik, Béla Ráczkevi, Péter Rácz, István Rigó, Melinda Szalóki, András Szenes, Ádám Takács, Csaba Tóth, Emese Tóth, Dávid Vass, Miklós Veres, Shereen Zangna

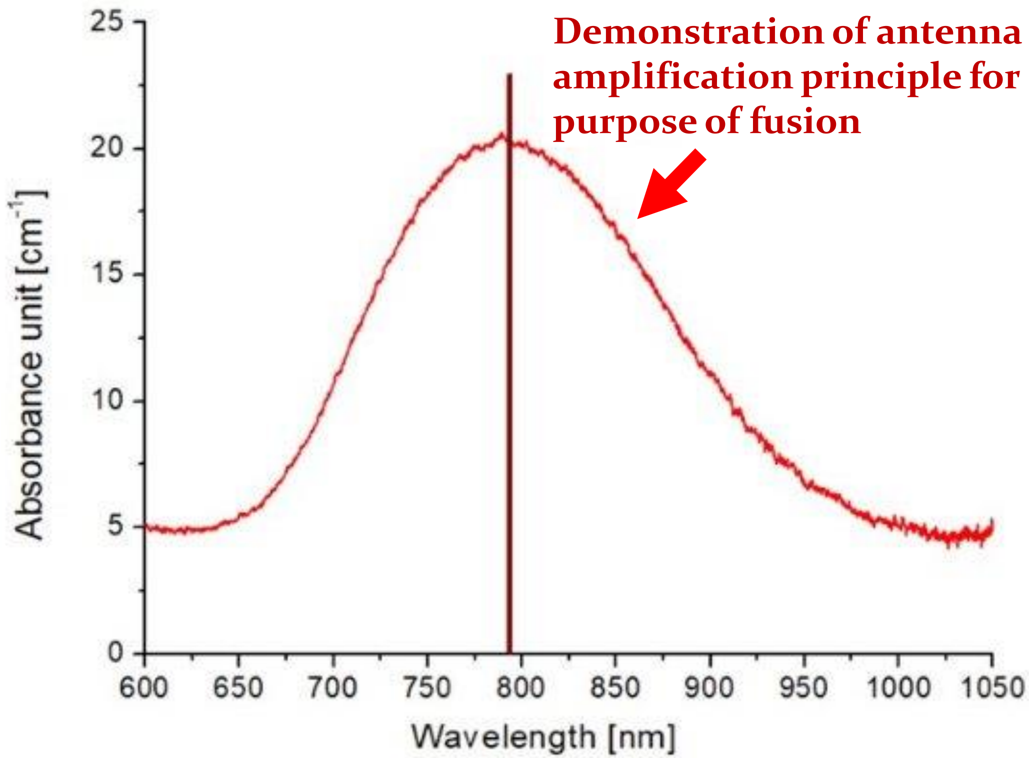
The NAPlife plasmonic fusion project

UDMA polymer with resonant gold nano-rods

Gold nano-rods embedded in polymer matrix: Transmission electron microscope image; insert shows actual nano-rods

Actual absorption curve for nano composites measured by optical spectroscopy. The absorption peak is tuned to resonate with laser wavelength at 795 nm





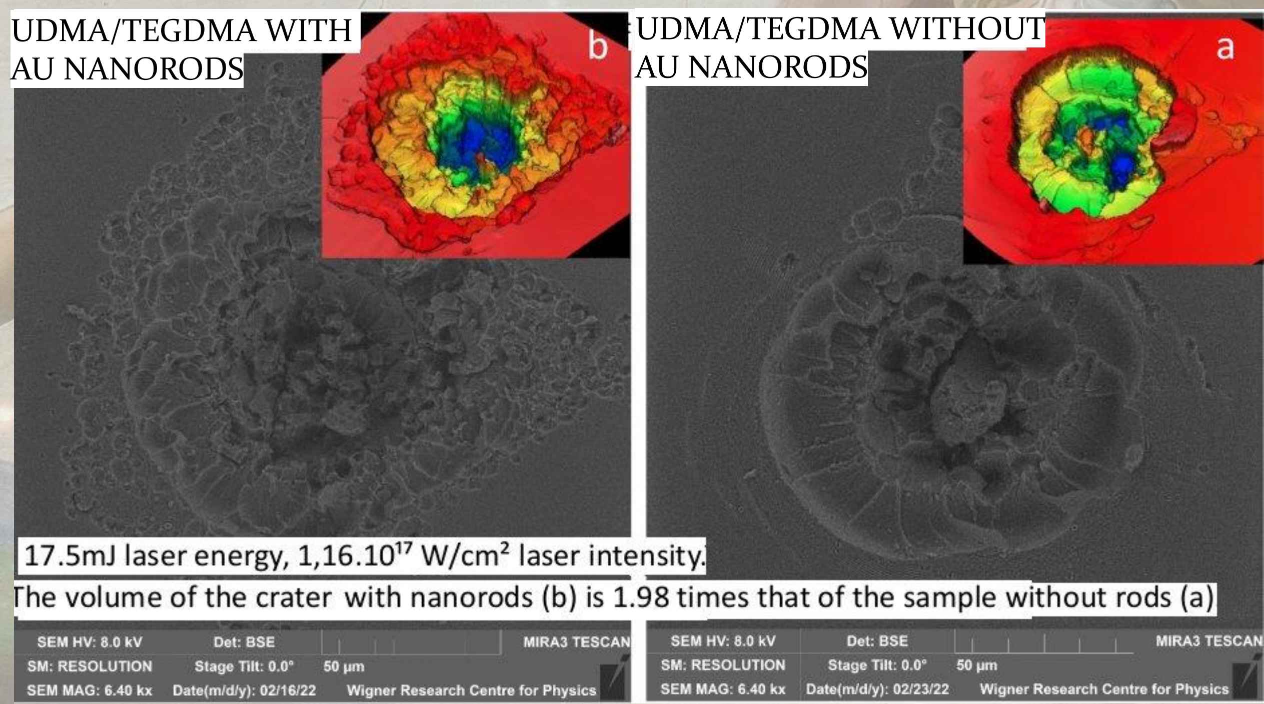
The NAPlife plasmonic fusion project

Three diagnostic methods for nuclear reactions

1. In prior laser fusion experiments detection of **helium production** played a pivotal role. This will be accomplished by the (laser-induced breakdown spectroscopy) LIBS study of plasma plumes emerging from the crater drilled by a laser shot into the polymer target. This can be supported by a mass spectrometry measurement of the plume compounds. Information about the alpha energy spectrum can be obtained from analysis of CR39 passive detectors.

2. The study of **deuterium content** is addressed by Raman scattering on the reaction crater surface.

3. The novel **energy production** measurement is achieved in the study of crater morphology: any energy production comparable in magnitude to the laser shot energy will be measured in terms of the quantity of material ejected. As a reminder, one Joule of energy corresponds to approximately 10^{12} fusion reactions. Polymer micro-structure damage relates to fusion product impacts, compare pB fusion CR39 detectors.



17.5mJ laser energy, $1{,}16.10^{17}$ W/cm^2 laser intensity.

The volume of the crater with nanorods (b) is 1.98 times that of the sample without rods (a)

Summary

- Early successes with muon catalyzed fusion clouded by use of weapon grade dt-cycle.
- Non-equilibrium short pulse laser driven environments have been recognized as the key ingredient allowing realization of nuclear fusion energy production
- Even milli-Joule pulses with near/sub femto-second pulse lengths with an extremely high contrast laser pulse profile (pulse length at wavelength scale) should create required fusion conditions in the context of nano-rod amplified targets.

Future Research

a) study of laser pulse EM interaction with nano-antennas: Domain of strong field physics

b) development of multiple component aneutronic chain fusion: Domain of nuclear physics

c) development of ignition nano-target geometry: Domain of numerical modeling / applied math

- I thank **Ryszard Gajewski** for infecting me with the desire to realize table-top usable fusion.

- I thank: **Steven E Jones** for happy years of collaboration in muon catalyzed fusion; **Christine Labaune** for her great leadership and dedication to laser driven non-equilibrium pB fusion.

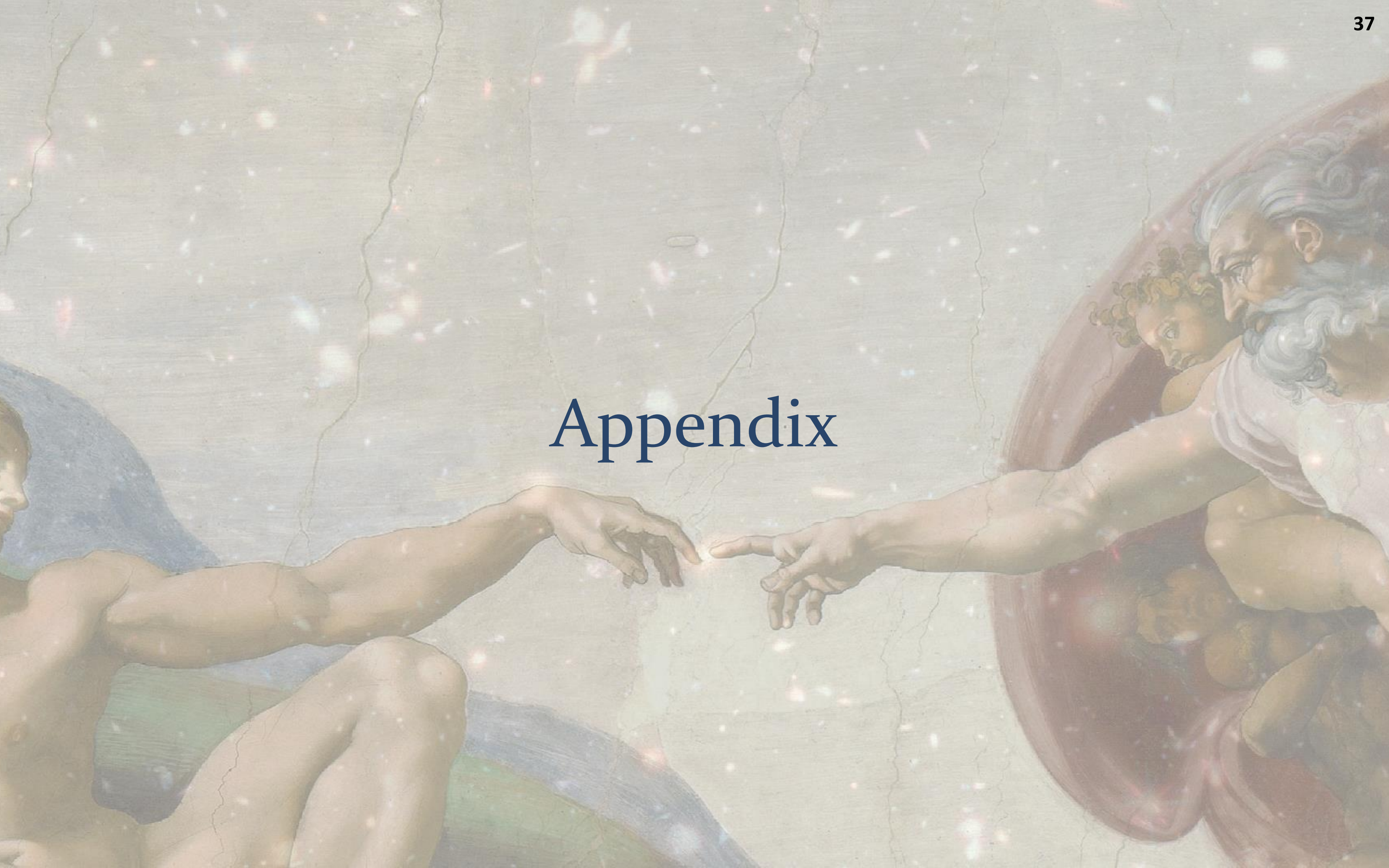
- I thank: **László Csernai** for his persistent multi-year effort in drawing my attention to plasmonic fusion; **L. C.**, **Tamás Biró**, **Norbert Kroó** for teaching me plasmonic fusion; I thank all of them and **Péter Lévai** for their kind hospitality in Budapest sponsored by the **Fullbright Foundation** with a travelling professor award and allowing my encounter with the plasmonic fusion project.

- I thank **Andrew Steinmetz** for interest in, and kind assistance with preparation of this talk.

Thank you for your attention!

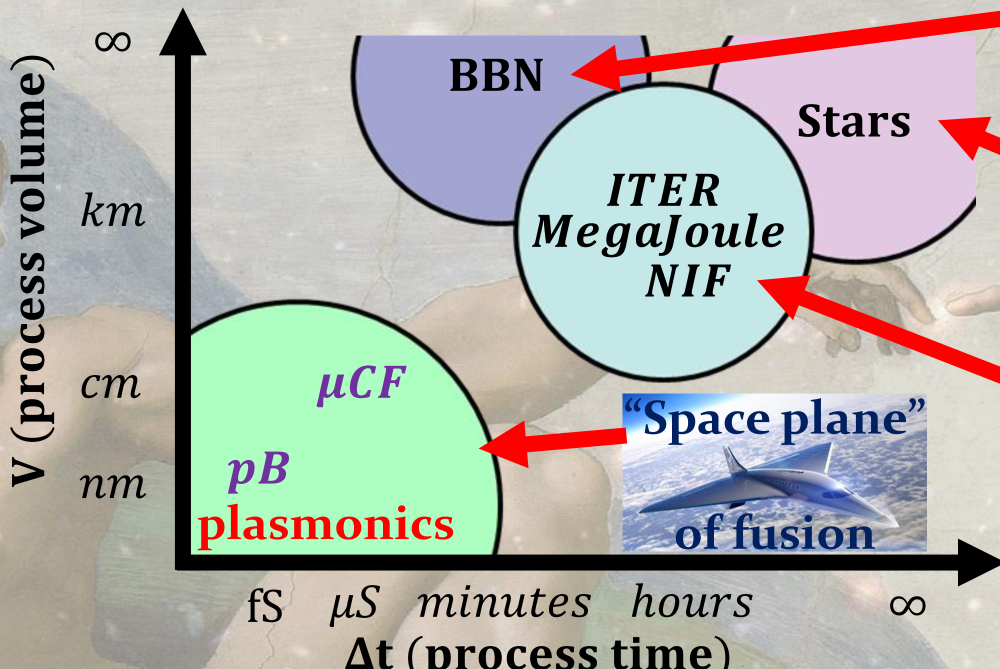
Johann Rafelski

Appendix



There are many different fusion reactors natural and (planned) manmade

Can we facilitate nuclear fusion via a different path as compared to early Universe Big Bang nucleosynthesis (BBN) or stellar core reactors?



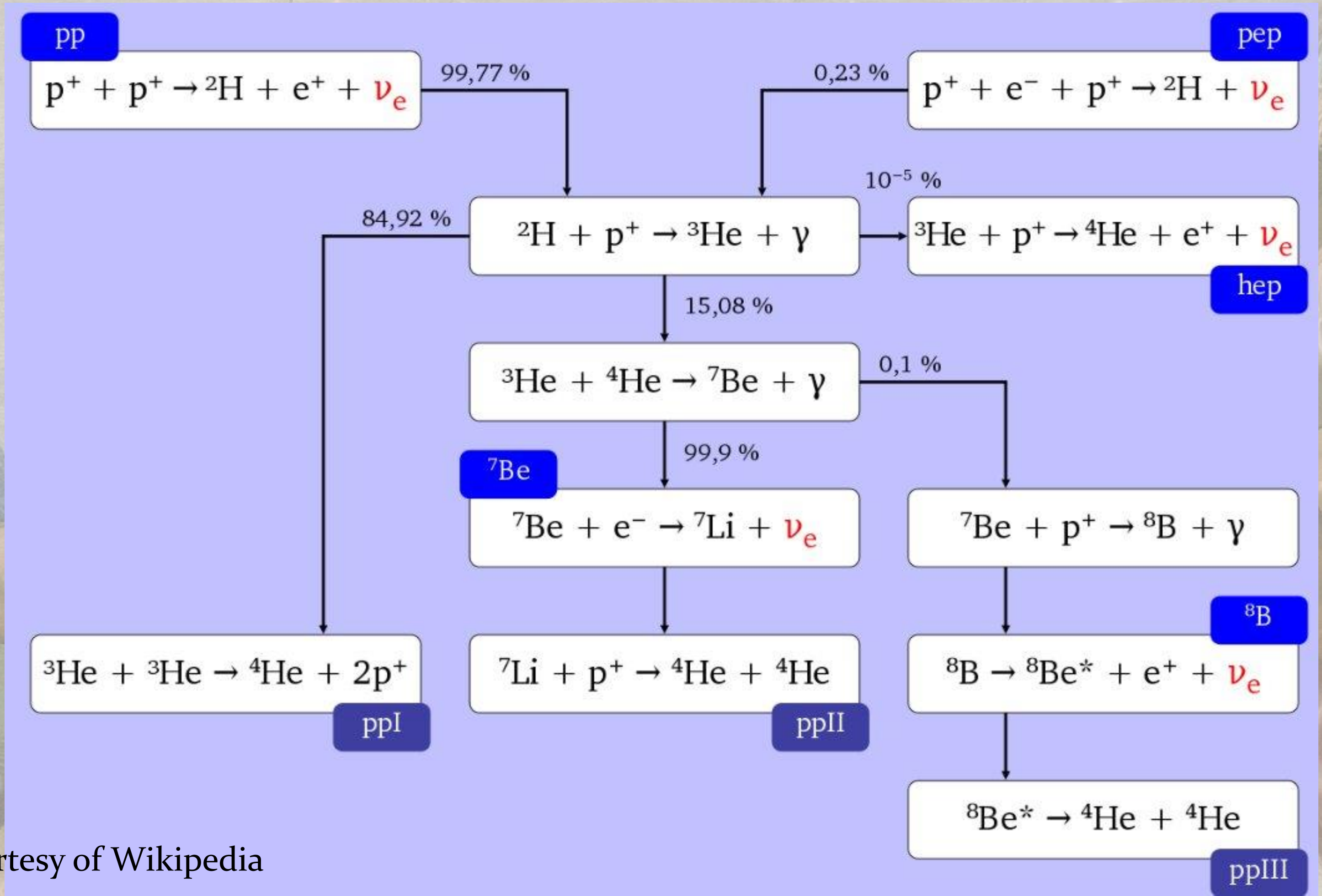
BBN in a homogenous thermally equilibrated plasma which is dynamic and expands over time.

Most stellar nucleosynthesis is an equilibrium process which is continuous and stable over large periods of time.

Some larger manmade fusion reactors are designed to operate for short pulsed periods of time.

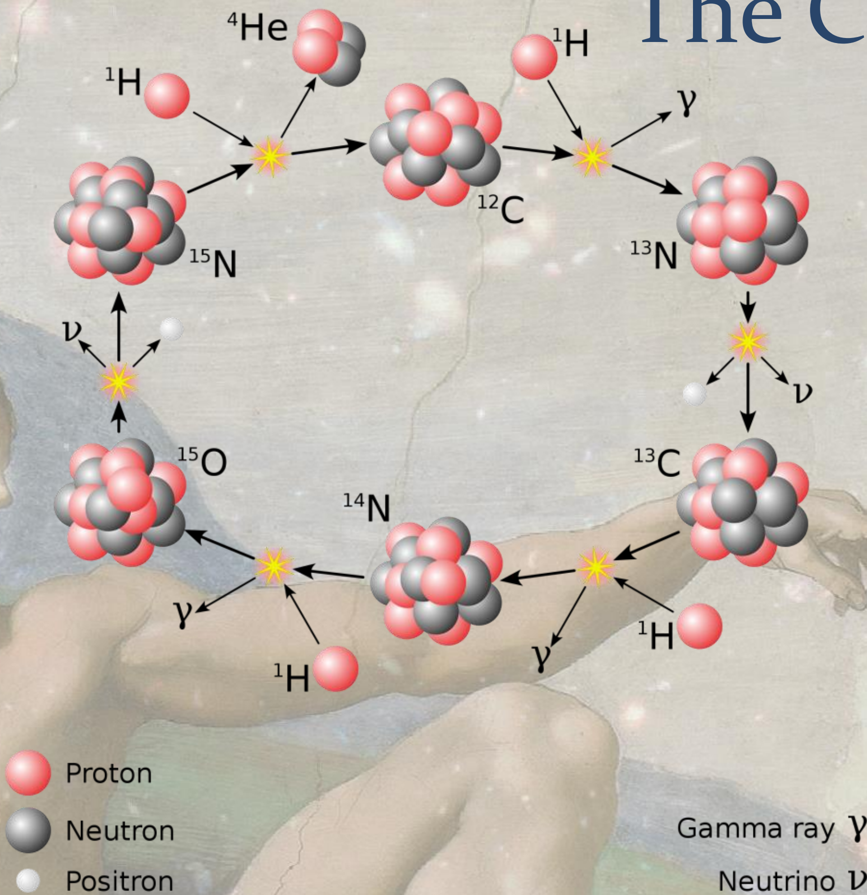
Muon-catalyzed fusion (μCF) Proton-Boron fusion (pB)

The proton-proton chain in detail

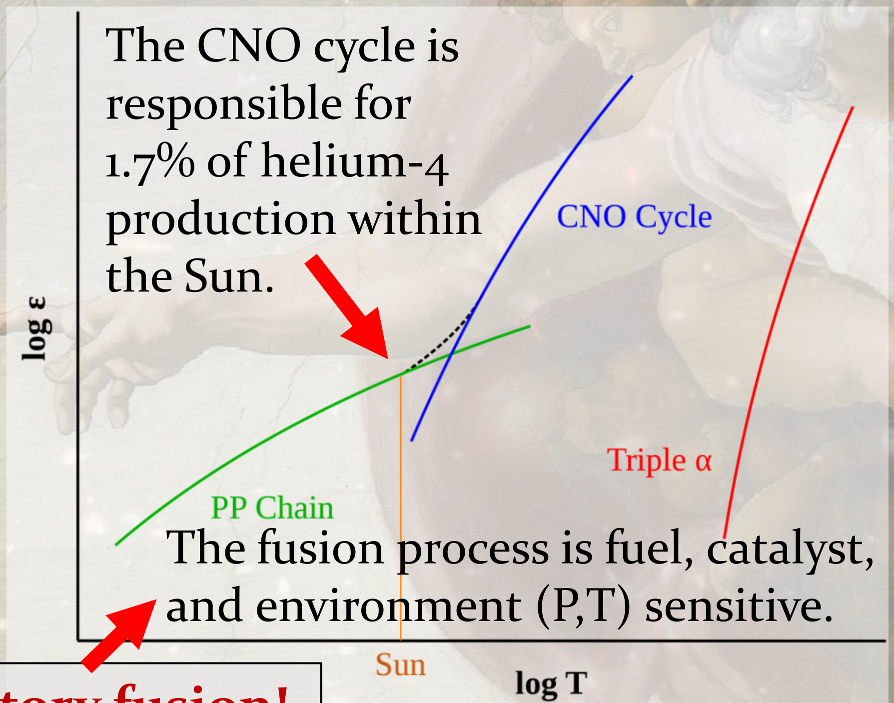


Graphic courtesy of Wikipedia

Secondary power source of our Sun: The CNO cycle



The CNO process is more important for massive stars and overtakes the PP chain for stars above 1.3 solar masses.



The fusion process is fuel, catalyst, and environment (P,T) sensitive.

Graphics courtesy of Wikipedia

Lesson for laboratory fusion!

Part III: Manmade fusion awakening

- III-A: ITER: International Thermonuclear Experimental "Reactor" (Since Oct 2007 in France: China, EU+, India, Japan, S Korea, Russia, USA)
  ITER is a steady state device.
- III-B: Inertial-confinement fusion:
  i. with lasers (NIF, Omega)   ii. with heavy ions (GSI) **inactive**

France=MegaJoule; seeks to ignite a small drop containing dt by a high-powered laser beam assembly. This is an imitation of nuclear H-bomb explosions.

Processes outside the thermal regime:

- III-C: Muon Catalyzed Fusion

J.D. Jackson reminisces: **Luis Alvarez** and colleagues discovered muon-catalyzed fusion of hydrogen isotopes by chance in late 1956. On sabbatical leave at Princeton University during that year, I read the first public announcement of the discovery at the end of December in that well-known scientific journal, The New York Times. A nuclear theorist by prior training, I was intrigued enough in the phenomenon to begin some calculations.

Jackson, J.D. A Personal Adventure in Muon-Catalyzed Fusion. Phys. Perspect. 12, 74–88 (2010). https://doi.org/10.1007/s00016-009-0006-9

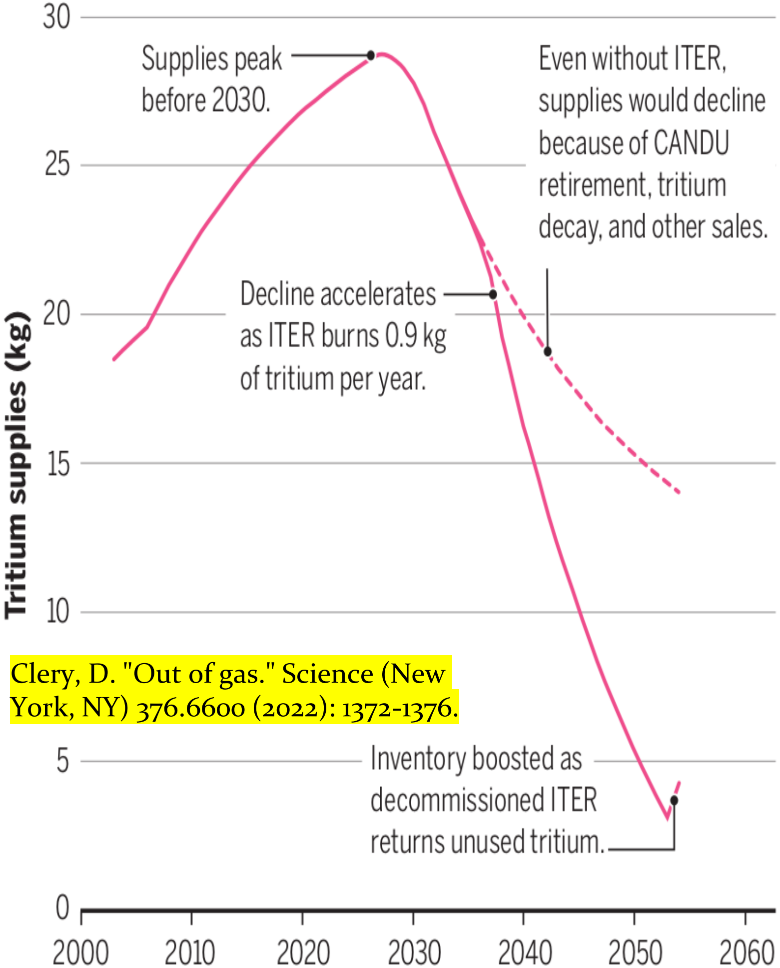
- III-D: Pulsed laser aneutronic pB fusion

Belyaev, V.S.; et al. (2005). "Observation of neutronless fusion reactions in picosecond laser plasmas" . Physical Review E. 72 (2): 026406. doi:10.1103/physreve.72.026406

- III-E: Plasmonic fusion (with pulsed lasers)

Begins in 2021: NAPlife project. Concentrations of light energy with nanorods: Antennas for light!

The few kilograms of commercially available tritium come from CANDU plants, a type of nuclear reactor in Canada and South Korea. According to ITER projections, supplies will peak this decade, then begin a steady decline that will accelerate when ITER begins burning tritium.



Clery, D. "Out of gas." Science (New York, NY) 376.6600 (2022): 1372-1376.

The trouble with tritium supply

$$A = \frac{C}{s} = 6.24 \times 10^{18}\,\frac{\text{electrons}}{\text{second}}$$

$$\mathrm{W} = \mathrm{VA} = 6.24 \times 10^{18}\ \mathrm{eV/s}$$

$$\#\text{ of fusions to produce 1 W} = \frac{6.24 \times 10^{18}\,\frac{\mathrm{eV}}{\mathrm{s}}}{17.6\ \mathrm{MeV}}$$

$$\mathbf{1\ W \mathrel{\widehat{=}} 3.55 \times 10^{11}\,\frac{dt\ fusions}{second}}$$

One 1 GW electrical power reactor needs to produce about 2.8 GW thermal power and this requires 10^{21} dt-fusions per second. Per year this amounts to

$$\#\text{ of fusion to run a reactor for 1 year} = 3.15 \times 10^{28}$$

which is **160 kg of tritium per year**.

$$6.02 \times 10^{23}\ \text{tritons} \mathrel{\widehat{=}} 3\ \text{grams}$$

Different μCF hydrogen fusion processes

Here are all the muon-catalyzed fusion processes with hydrogen, but only the dt-fusion processes can be cycled many hundreds of times per muon.

MuCF hydrogen fusion reactions.

Reaction	S-wave	P-wave	Products
$p + d \xrightarrow{(\mu)}$	$\sim .84\%$		^3He (5.4 keV)+γ (5.48 MeV)
	$\sim 16\%$		^3He (0.20 MeV)+μ (5.29 MeV)
$d + d \xrightarrow{(\mu)}$	$\sim 52\%$	42%	t (1.01 MeV)+p (3.02 MeV)
	$\sim 48\%$	58%	^3He (0.82 MeV)+n (2.45 MeV)
$p + t \xrightarrow{(\mu)}$			^4He (52 keV)+γ (19.76 MeV)
$d + t \xrightarrow{(\mu)}$			^4He (3.56 MeV)+n (14.03 MeV)
$t + t \xrightarrow{(\mu)}$			$^4He + n + n$ (11.33 MeV)

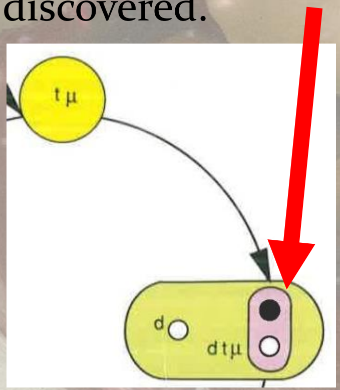
Search for aneutronic μCF All possible light element fusion reactions

Muon catalysed fusion

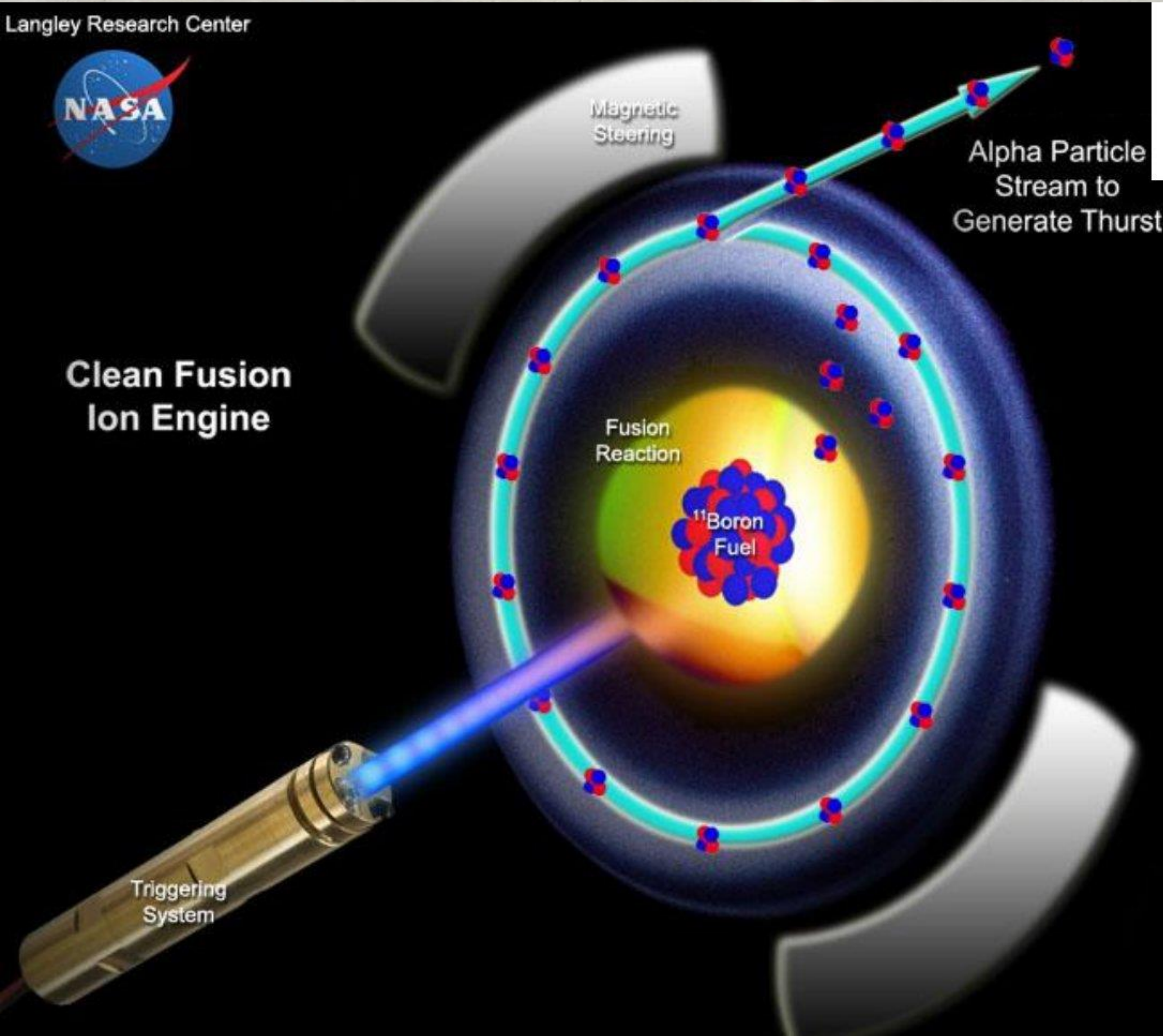
Q values (MeV) of the fusion reactions, reduced mass μ (MeV) of the nuclear system, 1sσ penetration constant $D_{1s\sigma}$, and an estimate of the reduced direct nuclear reaction rate $\tilde{\lambda}_f(s^{-1})$. 'Optimistic' and 'pessimistic' values of 0.5 and 1 were selected for ε, the optimistic values appearing in parentheses. Symmetry and quantum number selection rules have been disregarded.

Reaction	Q	μ	$\log(D_{1s\sigma})$	$\log(\tilde{\lambda}_f)$	Reaction	Q	μ	$\log(D_{1s\sigma})$	$\log(\tilde{\lambda}_f)$
^{2}H + p	6	625	−5 (−3)	13 (15)	^{10}B + p	9	852	−6 (−6)	12 (13)
^{2}H + d	24	938	−6 (−4)	12 (14)	^{10}B + d	25	1562	−8 (−8)	10 (11)
^{3}H + p	20	703	−5 (−3)	12 (15)	^{10}B + t	24	2159	−10 (−9)	8 (9)
^{3}H + d	17	1125	−7 (−4)	11 (14)	^{11}B + p	16	860	−6 (−6)	12 (13)
^{3}H + t	12	1404	−8 (−5)	10 (13)	^{11}B + d	19	1586	−8 (−8)	10 (11)
^{3}He + d	17	1125	−7 (−5)	11 (13)	^{11}B + t	21	2205	−10 (−9)	8 (9)
^{3}He + t	16	1404	−7 (−6)	11 (12)	^{12}C + p	2	866	−6 (−6)	12 (13)
^{4}He + d	2	1248	−7 (−5)	11 (13)	^{12}C + d	10	1606	−9 (−8)	10 (10)
^{4}He + t	3	1602	−8 (−6)	10 (12)	^{12}C + t	15	2245	−10 (−9)	8 (9)
^{6}Li + p	6	804	−6 (−5)	12 (13)	^{13}C + p	8	871	−6 (−6)	12 (13)
^{6}Li + d	22	1405	−8 (−6)	10 (12)	^{13}C + d	16	1624	−9 (−8)	10 (10)
^{6}Li + t	18	1871	−9 (−8)	9 (11)	^{13}C + t	13	2280	−10 (−10)	8 (9)
^{7}Li + p	17	820	−6 (−5)	12 (13)	^{14}C + p	10	875	−6 (−6)	12 (13)
^{7}Li + d	17	1457	−8 (−7)	10 (12)	^{14}C + d	11	1640	−9 (−8)	10 (10)
^{7}Li + t	17	1964	−9 (−8)	9 (10)	^{14}C + t	10	2311	−10 (−10)	8 (9)
^{9}Be + p		844	−6 (−5)	12 (13)	^{14}N + p	7	875	−6 (−6)	12 (13)
^{9}Be + d	16	1533	−8 (−7)	10 (11)	^{14}N + d	21	1640	−9 (−8)	10 (10)
^{10}Be + t	13	2105	−10 (−9)	8 (10)	^{14}N + t	19	2311	−11 (−10)	8 (8)
^{10}Be + p	11	853	−6 (−5)	12 (13)	^{15}N + p	12	879	−6 (−6)	12 (13)
^{10}Be + d	13	1562	−8 (−7)	10 (11)	^{15}N + d	14	1654	−9 (−8)	10 (10)
^{10}Be + t	11	2159	−10 (−9)	8 (9)	^{15}N + t	16	2339	−11 (−10)	8 (8)

Much work can still be done in this field!
Resonant mesomolecular processes would need to be discovered.



Muon catalysed fusion of nuclei with Z>1, D Harley et al (1990) J. Phys. G: Nucl. Part. Phys. 16 (2) p281 https://doi.org/10.1088/0954-3899/16/2/017



Advanced Fusion Reactors for Space Propulsion and Power Systems

John J. Chapman, NASA, Langley Research Center

2011

Advanced clean fusion ion engine system uses scientifically proven concepts to offer a unique solution to space applications. Abundantly available, Boron-11 fuel undergoes transmutation via a pulsed p-B11 plasma process to produce thrust in a novel & efficient fashion. Nuclear gain enables a dramatic performance increase as compared to existing ionic propulsion and power technology. Efficiency improvements are due to delivery of high velocity ions from plasma to exhaust while eliminating the customary radioactive isotopes as fuel stocks and reaction by-products

Why boron-nitride?

1. Chain of sustained reactions: Micro-explosions.
2. Boron-nitrides forms Buckyball nanostructures akin to C_{60}
3. Change of fuel, but otherwise same two-laser process.

OPEN

Laser-initiated primary and secondary nuclear reactions in Boron-Nitride

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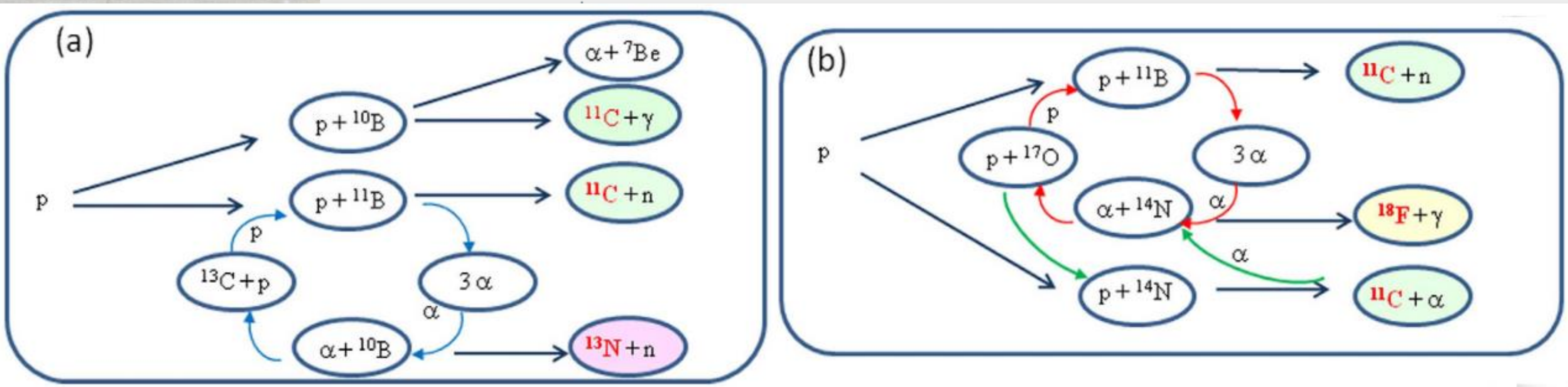
Published: 17 February 2016

C. Labaune[1], C. Baccou[1], V. Yahia[1], C. Neuville[1] & J. Rafelski[2]

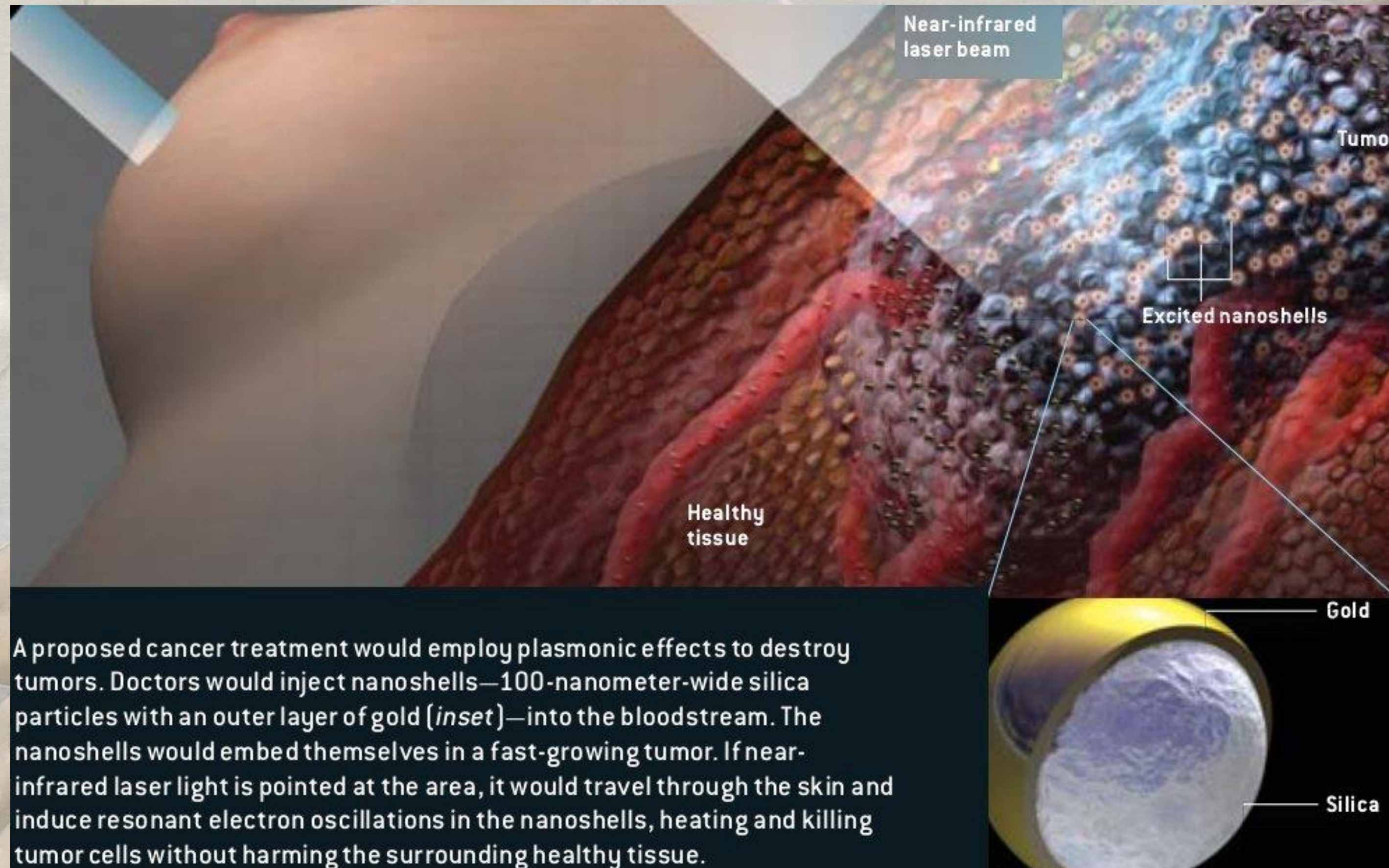
Nuclear reactions initiated by laser-accelerated particle beams are a promising new approach to many applications, from medical radioisotopes to aneutronic energy production. We present results demonstrating the occurrence of secondary nuclear reactions, initiated by the primary nuclear reaction products, using multicomponent targets composed of either natural boron (B) or natural boron nitride (BN). The primary proton-boron reaction ($p + {}^{11}B \rightarrow 3\alpha + 8.7$ MeV), is one of the most attractive aneutronic fusion reaction. We report radioactive decay signatures in targets irradiated at the Elfie laser facility by laser-accelerated particle beams which we interpret as due to secondary reactions induced by alpha (α) particles produced in the primary reactions. Use of a second nanosecond laser beam, adequately synchronized with the short laser pulse to produce a plasma target, further enhanced the reaction rates. High rates and chains of reactions are essential for most applications.



Scheme of the primary and secondary nuclear reactions produced by the interaction between a laser-accelerated proton beam and (**a**) a natural boron target, (**b**) a boron-nitride target. In the case of the BN targets the reactions with ${}^{10}B$ can also occur but are not shown for clarity.

Technological applications of plasmonics phenomenon

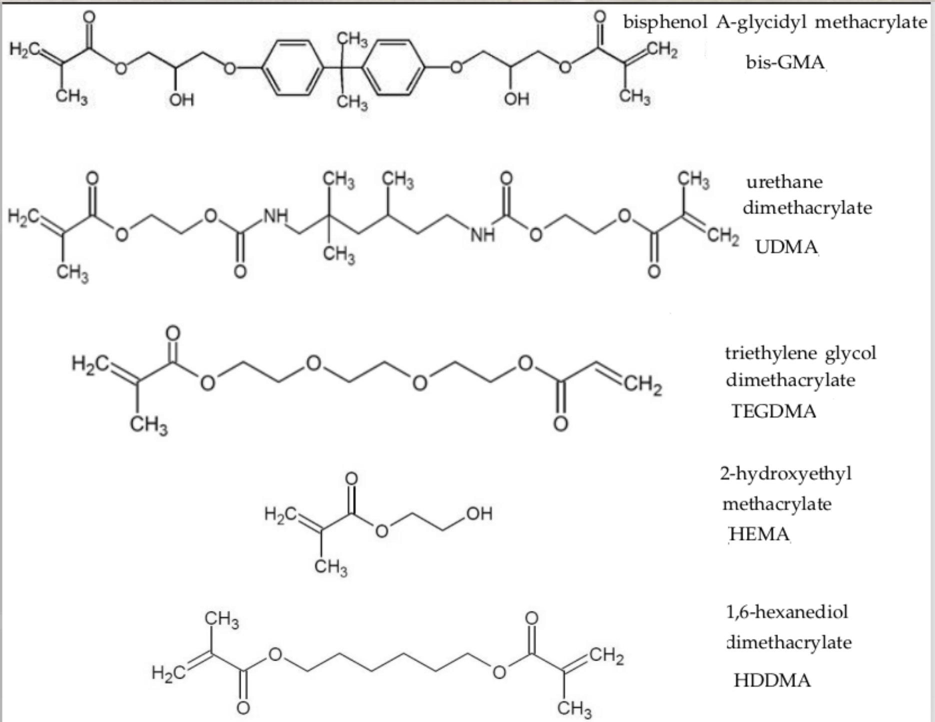
Owing to their unique laser light energy concentration properties nano particles are considered for:
1) Thermal treatment of cancer;
2) As enhancers of solar cell efficiency;
3) They are studied at the NAPlife research program in Hungary for their capability to enhance and stimulate laser induced nuclear fusion.
4) And many more…



The Promise of PLASMONICS; Harry A. Atwater Scientific American, Vol. 296, No. 4 (APRIL 2007), pp. 56-63

Plasmonic nanorods are embedded in a laser-light transparent resin

The media is initially a fluid monomer but is converted to a rigid polymer through polymerization. The most commonly used monomers for dental composites are bis-GMA and *UDMA*, which are diluted by a viscosity controller such as MMA, EGDMA or *TEGDMA* (most commonly used). Polymerization of dental composites may be achieved by chemical means (self-curing) or by external energy activation (heat or light).



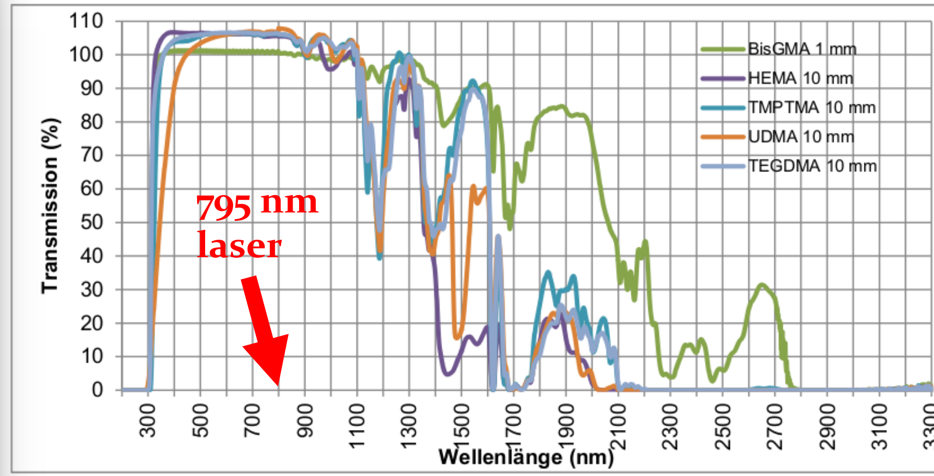
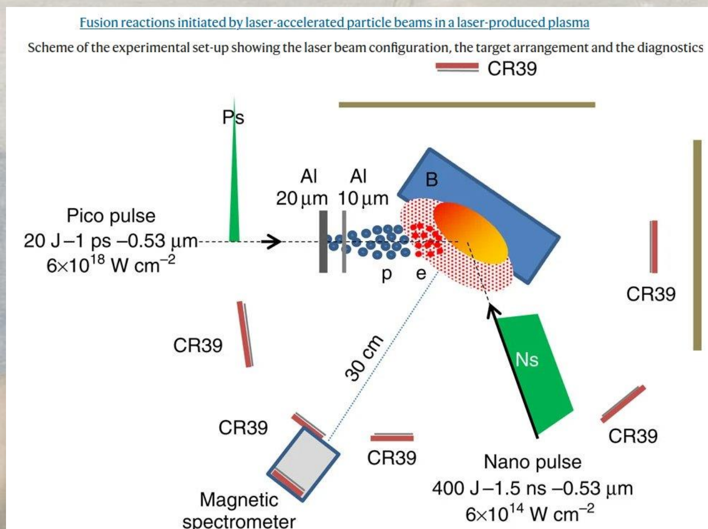


Abb. 36: **Transmissionsspektrum der Monomere BisGMA, HEMA, TMPTMA, UDMA und TEGDMA (Mittelwerte)** im Rahmen der spektroskopischen Untersuchung von Füllungs- und Befestigungswerkstoffen am Institut für Lasertechnologien in der Medizin und Messtechnik an der Universität Ulm von 2013 bis 2016. Die Probendicken sind rechts oben in der Legende genannt. (Abkürzungen: % = Prozent; nm = Nanometer; BisGMA = Bisphenol-A-glycidyl-methacrylat; HEMA = Hydroxymethylmethacrylat; TMPTMA = Trimethylpropan-Trimethacrylat; UDMA = Urethan-dimethacrylat; TEGDMA = Triethylenglycol-dimethacrylat; mm = Millimeter)

Comparing traditional thermal fusion from modern nuclear fusion approaches

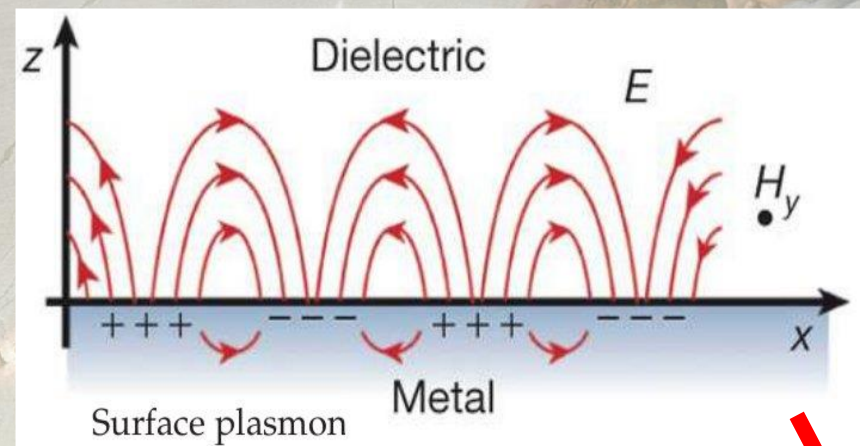
Modern nuclear fusion processes occur under inequilibrium conditions with the objective to spark a nano-fusion explosion which is short lived.

pB nuclear fusion

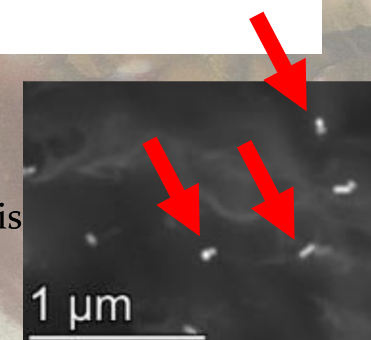


The long-pulsed nano-laser produces plasma and sweeps electrons away. The short-pulsed pico-laser produces a beam of reactant protons. Fusion reactions occur prior to protons reaching thermal equilibrium.

Plasmonic nuclear fusion



The nano-sized antenna are "energized" to an extreme degree by the incident laser and in the brief moment before the antenna is destroyed, the surface plasmons accelerate particles to required fusion conditions.

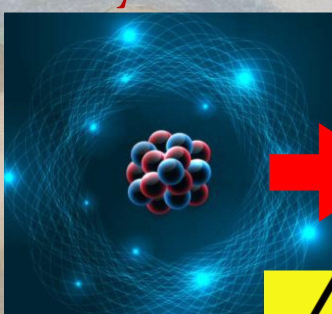


Comparing modern approaches

How close are we to "space plane" fusion in both the figurative and literal sense? How will we power the real future space planes that can travel across the solar system?

4,000 years

100 years



Recap:

- μCF opened the door to considering fusion processes outside the thermal regime
- pB laser driven fusion remains an essential technological exploration towards table-top fusion
- Plasmonic fusion satisfies all the requirements of truly table-top fusion:
  - Femto-attosecond high contrast laser pulse
  - Aneutronic
  - Different nuclear fuels can be attempted
  - Today exploring processes with scalable commercial laser technology
  - Transferable to **ELI-Alps** laser for large scale energy production

What is this talk about?

- The different nuclear fusion processes in nature
- Pros and con of man-made nuclear fusion
- Explanation of principles and ideas in fusion processes
- The search and economic interest in fusion
- The windy path to novel realizations of fusion
- The future of nuclear fusion energy (pB, plasmonics, …)

What is this talk <u>not</u> about?

- Not an introduction to nuclear reaction theory
- Not an introduction to high-intensity short-pulsed laser physics
- Not an introduction to plasmonic physics mechanisms
- Not a sales pitch