Magnetic field sources for aneutronic fusion

Rationale, overview, and development roadmap

June 2020

Executive Summary

Silent ecosystem revolution that cannot be fully addressed by transition to renewables is underway

- The world's ecosystem is challenged by growing population and resource scarcity impeding large-scale sea water desalination, access to energy, clean waste recycling and food security; climate change puts even stronger pressure on fragile ecosystems, causing mass migrations, conflicts and wars; abrupt ecosystem change examples include Aral Sea, Syria, Dead Sea…
- Non-fossil energy sources such as renewables and nuclear power cannot fully address these challenges as they account for just 3.6% and 4.4% of global energy supply respectively; despite widespread hopes and extensive state subsidies for renewables, their present growth rates are limited; nuclear industry has seen its growth slashed in the aftermath of Fukushima accident (2011); renewables are still way too costly, especially for large-scale applications: for instance, no single water desalination plant sustains full cost of renewable electricity

Aneutronic fusion has the potential for low-cost energy and has recently seen huge experimental & theoretical progress

- Advent of aneutronic proton-boron fusion with its potential for high energy density, compactness, and mobility could address resource scarcity and climate challenges
- By 2018 measured reaction yields improved $\times 10^{7.6}$ times since first experiments back in 2005 by Belyaev et al; however, reaction gain at $\times 10^{-3.4}$ of ignition laser beam energy (Giuffrida 2018) still falls short of breakeven and neutronic Deuterium Tritium fusion gains of $\times 10^{-1.4}$ achieved at NIF (Le Pape 2018)
- On theoretical front, magnetically confined aneutronic fusion model was proposed by Hora and Lalousis (2014), promising gains up to $\times 10^{4}$ of ignition laser beam energy; a possibility of alpha-avalanche effect, with alpha particles transferring their energy in a chain reaction was modelled by Eliezer (2016) and Belloni (2018)
- Based on historic gain evolution, breakeven demonstration could be achieved by ~2026, likely driven by launch of new high-power laser facilities (ELI, PETAL…)

To speed up its development we propose an innovative approach to R&D

- Miniaturization is key to successful experimental demonstration, taking into account large footprint and cost of fusion facilities (e.g. NIF, ITER…)
- According to the theory of Hora et al, among the 5 value chain steps (fuel, magnetic confinement, ignition laser, ignition process, energy conversion to grid), key driver of miniaturization leading to successful experiment shall be ultra-strong / ultra-compact magnetic field confinement
- Recently discovered ultra-strong magnetic fields $\sim 10^{4}$ T are promising dramatic reduction in footprint and cost of demonstration facilities; such ultra-strong $\sim 10^{4}$ T, ~ ns duration magnetic fields, able to confine reaction plasmas in a compact volume can be produced by capacitor coil discharge
- Proposed innovation is based on a new CNT Copper / N-doped Graphene Copper composite magnetic coil with record current carrying capacity and ultralow resistivity: innovative material potentially allows the coil to withstand $\times 10^{2}$ higher currents vs. Copper and increase the efficiency of magnetic field generation

Practical roadmap aligned with the approach will reduce risks and increase the likelihood of breakeven demonstration

- Realize a "Proof of principle" experiment reducing overall program risk: test copper composite coil, demonstrate ultra-compact ~1,000 T magnetic fields in a lab; if successful, realize "Proof of impact" experiment applying Copper composite coil to aneutronic fusion at high-power laser facilities (ELI, PETAL…) using existing pulsed power sources
- Design "Minimum Viable Product" external magnetic field loop for breakeven aneutronic fusion yield demonstration at existing laser infrastructures (ELI, PETAL…)
- Following the MVP's successful demonstration proceed to proton-boron fusion commercialization

Silent ecosystem revolution underway

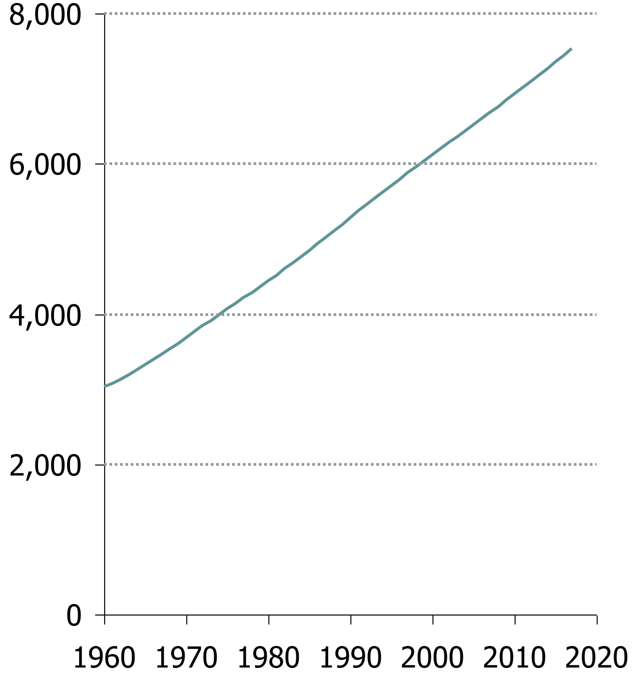
Aneutronic fusion potential

Innovative approach to R&D

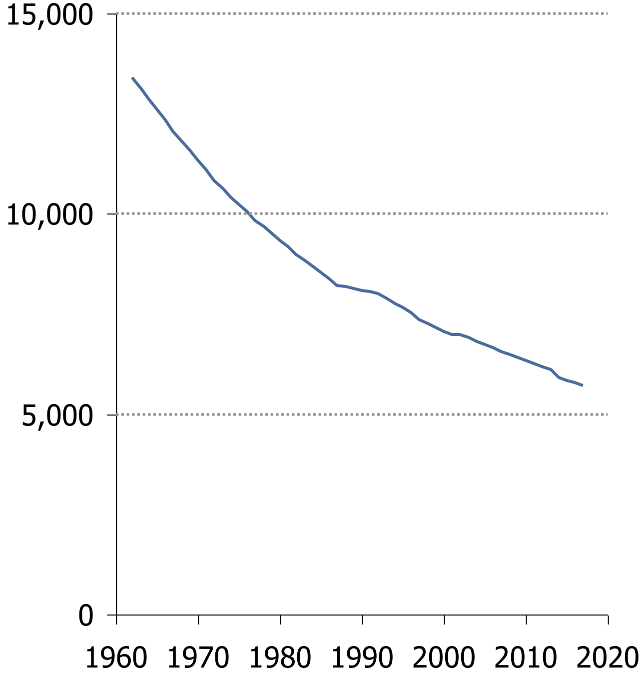
Practical / low-Risk / low-CapEx roadmap

The ecosystem is challenged by growing population and resource scarcity, aggravated by climate change

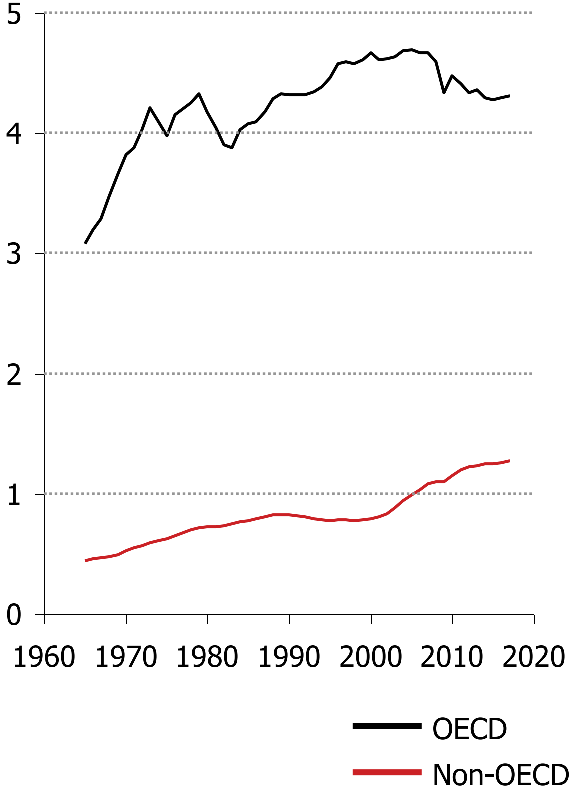
World's population
million inhabitants



Freshwater
resources / capita, m^3 p.a.

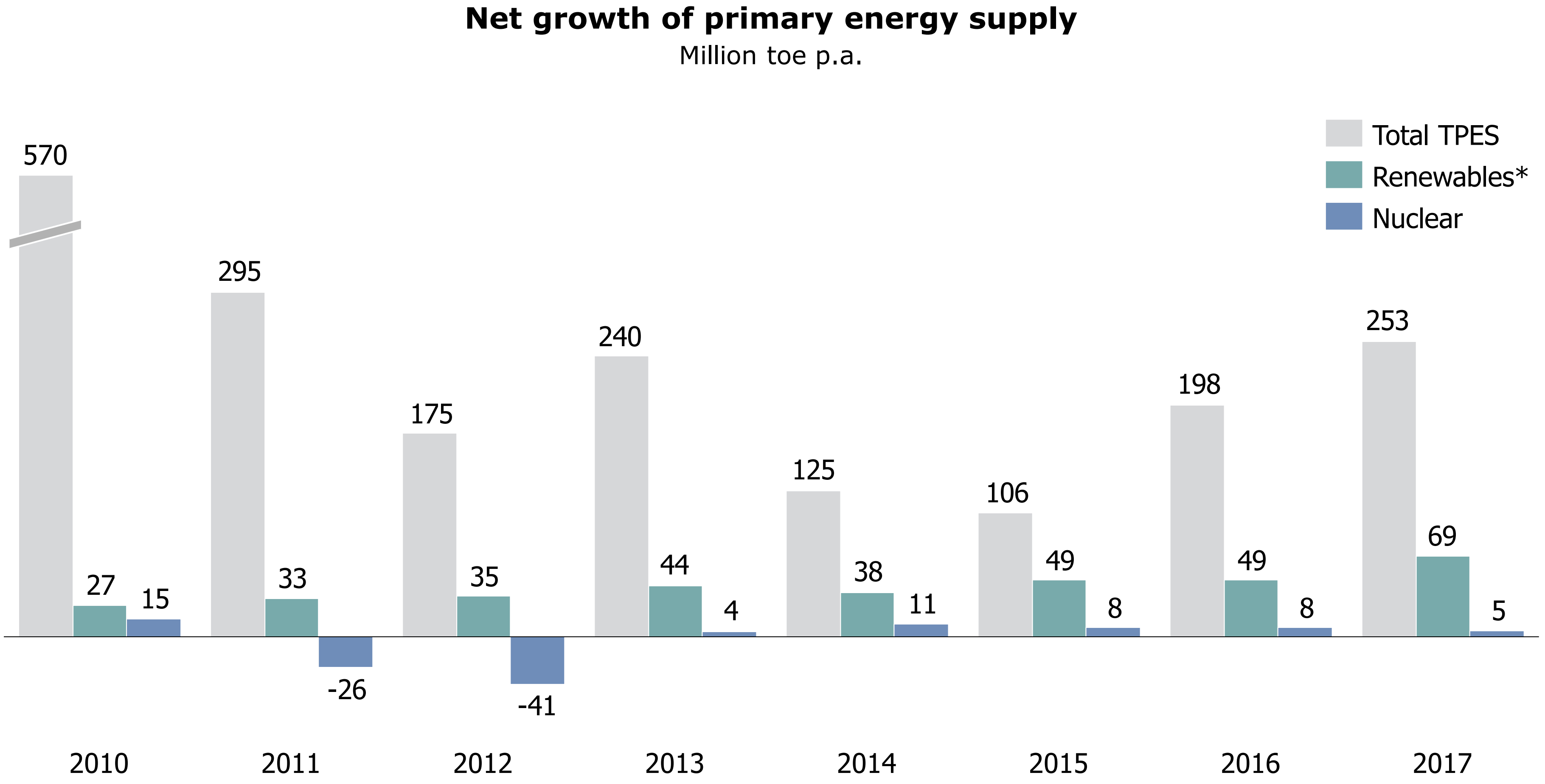


Primary energy supply
toe / capita p.a.



Source: World Bank, BP World Energy Review, 2018

Non-fossil energy sources such as renewables and nuclear power cannot fully address these challenges



Source: BP World Energy Review, 2018

Silent ecosystem revolution underway

Aneutronic fusion potential

Innovative approach to R&D

Practical / low-Risk / low-CapEx roadmap

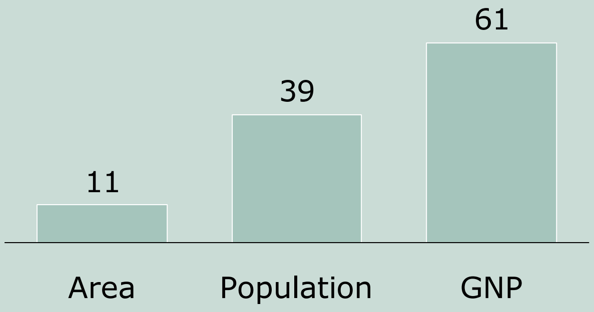
Advent of aneutronic fusion has the potential to dramatically expand the world-system’s frontier

Current world-system frontier

- Presently most of world’s population and economic activity is concentrated in coastal zones
- Inland zones are much less developed due to structural limitations: energy, logistics, infrastructures etc.
- Some applications (sea water desalination) prohibitively costly if powered by fossil fuels and / or renewables

Share of Coastal Areas

<100 km zone, % of World’s



Break energy limitations

Potential world-system frontier

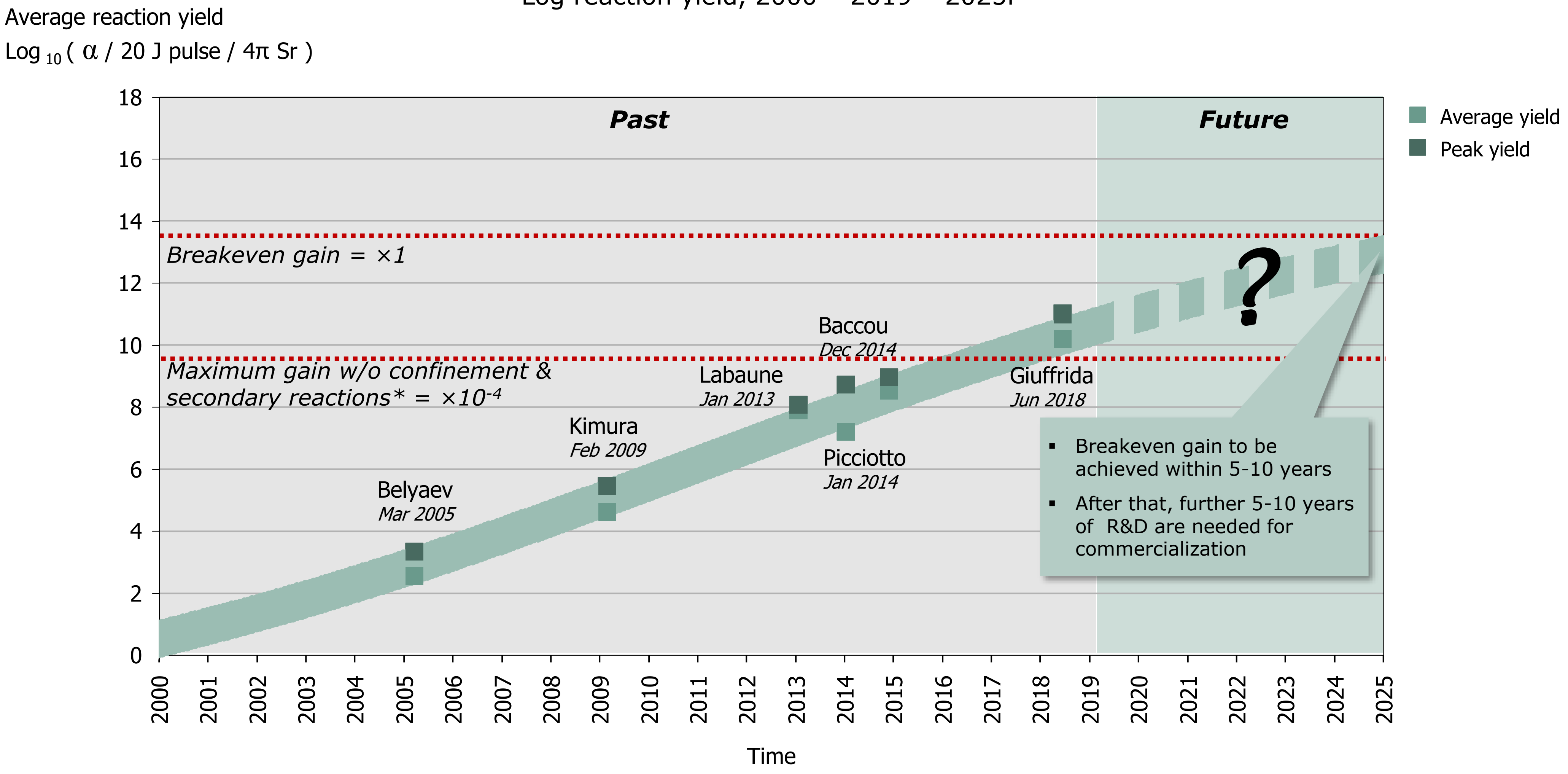
- Structural limitations could be broken by new energy sources with following properties:
  - High energy density
  - Safety for the environment
  - Carbon neutrality
  - Compact footprint
  - Mobile and independent from e.g. water cooling
- If aneutronic fusion proves to be viable, the frontier of the world-system will be dramatically expanded by the following applications:
  - Distributed power generation
  - Sea and brackish water desalination
  - Clean waste treatment
  - Transport
  - Direct distribution
  - etc.

Source: Millennium Ecosystem Assessment (2005)

Tangible experimental results of laser-driven aneutronic fusion have recently been demonstrated

S-Curve of $^{1}H^{11}B$ fusion experiments

Log reaction yield, 2000 – 2019 – 2025F



- Breakeven gain to be achieved within 5-10 years
- After that, further 5-10 years of R&D are needed for commercialization

* Theoretical model by Isidore Last, 11/04/2011

Source: Belyaev (2005), Kimura (2009), Labaune (2013), Picciotto (2014), Baccou (2015), Giuffrida (2018)

In parallel, theoretical progress delivered a model for high-gain aneutronic fusion by Hora / Lalousis / Eliezer

1972
- Bobin-Chu discovered **side-on ignition** of solid-state fusion fuel
- Criteria for **energy fluence** were defined, impossible to achieve at that time
- **Volume ignition** with thermal compression by laser was chosen as more feasible (high-CapEx National Ignition Facility / U.S., Laser Mega Joule / France)

1973
- Weaver-Zimmerman: Proton-boron fusion reaction found to produce **less radioactivity than burning coal** with 2 ppm of uranium

1985
- Strickland and Mourou invented Chirped Pulse Amplification, a technique to produce **high-power laser beams** by amplifying and then compressing pre-stretched pulse

1997
- Scheffel shows that proton-boron fusion under volume ignition is **10^5 more difficult to achieve** than deuterium-tritium

2002
- Hora and Badziak interpret **Sauerbrey's results in side-on ignition context**
- They theoretically show that non-linear acceleration of plasma blocks **satisfies energy fluence** conditions of Bobin-Chu (1972), $j > 10^{11}$ Amp/cm^2

1996
- **Non-linear force ultrahigh acceleration** of plasma blocks by laser pulses observed by Sauerbrey
- Key criteria for laser pulses: high-contrast $<10^{-8}$, $<10^{-12}$ s, single-mode

2008
- Hora, Malekynia readjust Bobin-Chu's energy fluence threshold for non-linear accelerated plasma **down by ×20**
- They take into account the inhibition factor and collective effect

2008
- Badziak experimentally verifies that non-linear acceleration of plasma blocks **satisfies energy fluence** conditions of Bobin-Chu (1972), $j > 10^{11}$ Amp/cm^2

2011
- Mourou initiates the ICAN, a project to develop compact, high avg. power, high quality, high efficiency **fibre lasers for scientific applications**

2011
- Hora theoretically shows that energy fluence threshold for side-on proton-boron ignition only $10^{0.6}$ higher vs. deuterium-tritium
- This is **strikingly easy** vs. volume ignition where threshold is higher by 10^5

2013
- Fujioka et al experimentally show what they believe is strongest ever **10^4 T, ns magnetic field** generated by laser hitting Cu capacitor coil
- Later in 2015 Santos experimentally corrects their result to **$10^{2.9}$ T**, ns magnetic field with **8% efficiency**

2014
- Hora proposes **spherical** proton-boron fuel geometry, ignited by **EW-ps laser pulse**
- Gain factor est. only 69

2014
- Lalousis proposes **cylindrical** fuel geometry, ignited by **30 PW-ps** laser pulse, confined by **10^4 T** magnetic field
- Est. predict a **gain factor of 500+** in 2 ns period
- However, he did not take into account the **full cost of producing 10^4 T field**

2015
- Moustaizis proposes an experiment at ELI-NP laser (Romania, expected by 2019) confined by **100+ T magnetic field** generated by capacitor bank discharge

2016
- Eliezer and Hora suggest reaction product alphas could generate **secondary** fusion reactions, resulting in **alpha-avalanche-multiplication**; Shmatov 2016 discards the idea, but Belloni 2018 defines specific conditions for alpha-avalanche

2016
- Labaune's analysis of $p^{11}B$ reaction products' isotopic composition proves secondary α are inducing further $p^{11}B$ fusion reactions

2019
- A new powerful laser **ELI** expected to become operational, providing the opportunity to verify the validity of Hora / Lalousis / Eliezer theory

1970 1975 1980 1985 1990 1995 2000 2005 2010 2011 2012 2013 2014 2015

Silent ecosystem revolution underway

Aneutronic fusion potential

Innovative approach to R&D

Practical / low-Risk / low-CapEx roadmap

Several R&D avenues exist…
Miniaturization is key to successful demonstration

PLASMA CONFINEMENT

	Project / Company	Country	Founded	Reaction	Mode	Footprint *m*	Funding *$m*
Electro static	Polywell / EMC2	U.S.	1985	Proton ^{11}Boron	Continuous	3	42
	Convergent Scientific Inc.	U.S.	2010	Deuterium Tritium	Continuous	1.2	0.1
Magnetic	ITER	France / Int'l	1985	Deuterium Tritium	Continuous	50	25,600
	MIT PSFC ARC	U.S.	2013	Deuterium Tritium	Continuous	7	4,000*
	Commonwealth Fusion Systems	U.S.	2018	Deuterium Tritium	Continuous	7	75 / 3,000 (2033)
	Lockheed Martin Skunk Works	U.S.	2011	Deuterium Tritium	Continuous	13	4
	TAE Technologies	U.S.	1998	Proton ^{11}Boron	Continuous	20	500
	Tokamak Energy	U.K.	2009	Deuterium Tritium	Continuous	3	15
	Max Planck IPP Wendelstein 7-X	Germany	1994	Deuterium Tritium	Continuous	11	1,360
Inertial	National Ignition Facility	U.S.	1997	Deuterium Tritium	Pulsed	340	3,500
	Laser MegaJoule	France	1999	Deuterium Tritium	Pulsed	300	4,220
Magneto Inertial	General Fusion	Canada	2002	Deuterium Tritium	Pulsed	3	97
	Helion Energy	U.S.	2009	Deuterium Deuterium	Pulsed	16	21
	Sorlox	U.S.	2010	Deuterium Tritium	Pulsed	<1	1
	MagLIF	U.S.	2010	Deuterium Tritium	Pulsed	1.1	3.8
	Lawrenceville Plasma Physics	U.S.	2003	Proton ^{11}Boron	Pulsed	<2	4.5
	HB11 Energy	**Australia**	**2017**	**Proton ^{11}Boron**	**Pulsed**	**2**	**---**

Commercial project Publicly-funded project ⬚ Low-CapEx magneto-inertial route

- Unique conditions required for fusion (pressure, temperature, confinement time) are naturally observed only in star interiors
- Most attempts to replicate such extreme conditions on Earth resulted in tremendous CapEx (ITER, NIF…) and delivered mediocre results
- Miniaturization of such extreme states of matter is key to successful experimental demonstration of breakeven fusion
- Among plasma confinement modes, hybrid magneto-inertial way promises to decrease the volume and footprint threshold for breakeven fusion and reduce CapEx
- Hybrid magneto-inertial plasma confinement requires pulsed ultra-strong magnetic field and ultra-intense ignition laser

* Federal government suspended funding of MIT PSFC ARC project in 2016

Source: Tomas Linden, Helsinki Institute of Physics, NST2016, web search

Key driver of miniaturization shall be ultra-strong / ultra-compact magnetic confinement

Aneutronic fusion "Value Chain"

Fuel Structure

- Fuel structure might impact the yield of alphas, increasing the probability of secondary fusion reactions
- Labaune (02/2016): 2.5× higher alpha yield for boron-nitride vs. pure boron fuel
- Giuffrida (06/2018): high alpha yield $10^{11.3}$ / 500 J pulse / Sr with structured boron nitride fuel and specific laser incidence angle

Magnetic Confinement

- Magnetic fields ~10^4 T are required to achieve breakeven gain in cylindrical geometry, acc. to Hora / Moustaizis (04/2016), excluding avalanche effect
- Currently copper electro magnets withstand from 10^2 (non-destructive) to $10^{2.9}$ T (destructive) magnetic fields
- Recently, new CNT Copper / N-doped Graphene Copper materials were proposed (Subramaniam 2016, Zheng 2018, Wang 2019), sustaining much higher ×10^2 current densities, ×13.3 lower resistivity vs. copper, which could lead to very strong magnetic fields by ultra-compact sub-mm single turn coils

Ignition Laser

- Laser pulse energy of 30 kJ is required to achieve breakeven gain in cylindrical geometry, acc. to Hora / Moustaizis (04/2016), excl. avalanche effect
- While there are many laser facilities with kJ-MJ pulse energies, none of them satisfy extreme pulse contrast, duration and quality criteria
- Recently constructed ELI Beamlines facility in Czech Republic with pulse energy of 1,500 J, contrast of 10^{-11} and pulse duration of 150 fs might serve as reliable experimental platform for aneutronic fusion tests

Ignition Process

- Fuel ignition process already patented by H. Hora
- Patents transferred to HB11 Energy Pty (Australia) for commercialization
- Limited potential to add more value
- Numerical simulations with particle-in-cell codes, e.g. OSIRIS v.2, shall be beneficial to build robust process model

Direct Energy Conversion

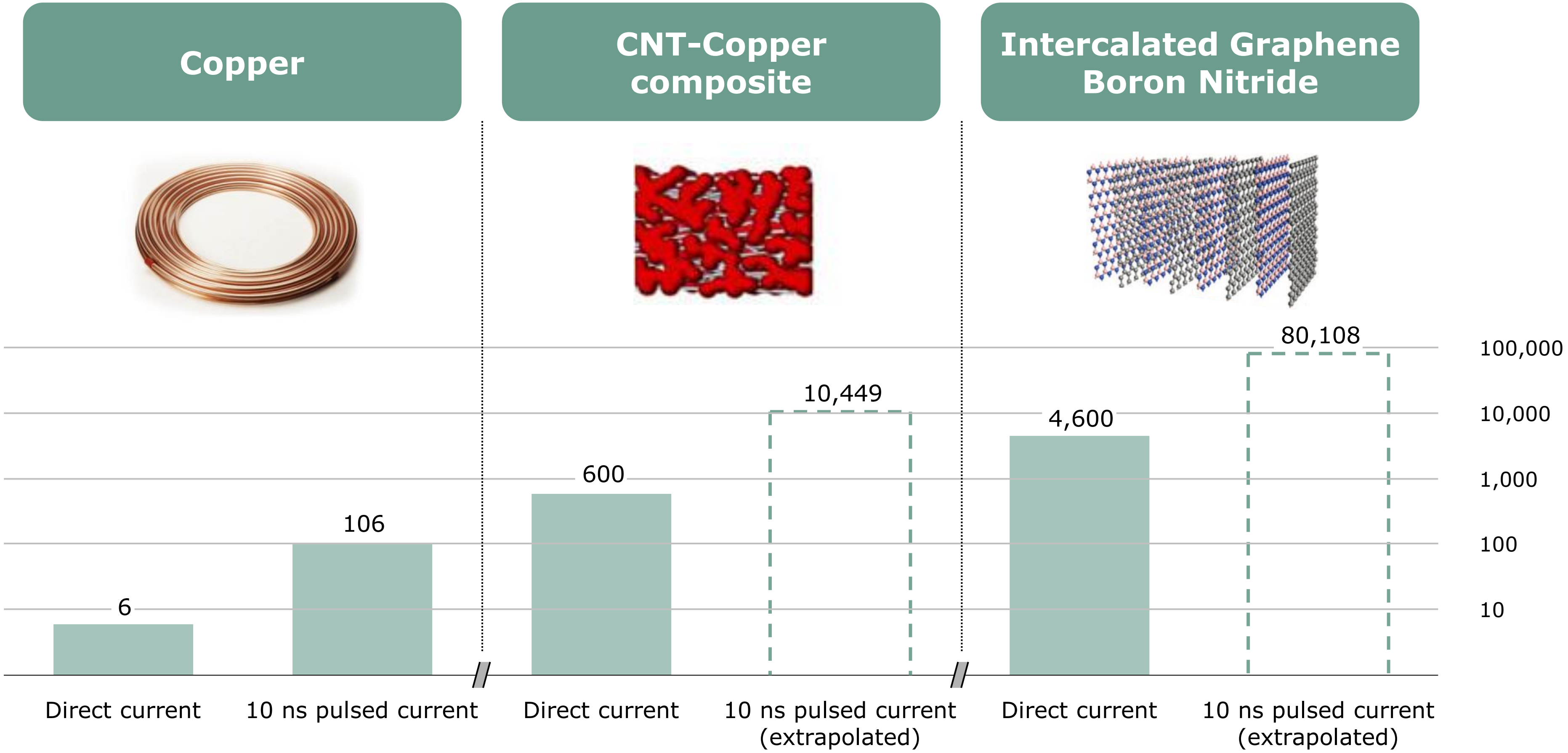
- Various patented direct conversion techniques exist (TWDEC, Inverse Cyclotron…)
- This step of the value chain is less risky and critical until breakeven fusion is demonstrated

Innovations 🟩

The innovation is based on CNT Copper / N-doped Graphene Copper coil with record current density and tensile strength generating ultra-strong magnetic fields

Current density

MA / cm^2, log scale



Source: Subramaniam (2013), Banerjee (1996), Li (2012), Magnite Technologies analysis

Silent ecosystem revolution underway

Aneutronic fusion potential

Innovative approach to R&D

Practical / low-Risk / low-CapEx roadmap

Short-term priorities

- Order CNT-Aluminum-Copper coil samples from China or reproduce according to the methodologies indicated in the relevant papers (Wang 2019, Zheng 2018)
- Test coil’s magnetic field generation properties in a European lab; if successful, publish paper with the results
- Apply for Horizon 2020 funding jointly with ELI Beamlines team
- Develop a “minimum viable product” – compact, non-destructive, mobile source of 1 kilotesla-scale magnetic fields to be sold to laser facilities in the EU and beyond

Prepare for the medium-term objective:
Breakeven thermonuclear fusion yield demonstration

Team

Alexis Komarov, CEO & Founder

- Following the graduation from Moscow State University, Alexis moved to Kyiv and started a career in a well-known local management and strategy consulting firm
- **Being fed up with senseless projects** that later brought huge losses to company's clients, Alexis lost motivation and got kicked out of his first job in 2007
- He then joined a small strategy & management consultancy ISTRATS led by a French expatriate in Kyiv. His first project for the heir to the former "Compagnie Universelle du Canal Maritime de Suez" **turned his thinking around**. He came to regard his mission as very much opposite to what he has been doing before: new creation vs. redistribution of existing resources, science vs. rule of thumb, risk aligned staged CapEx vs. high-CapEx high-risk approach etc
- During the following 12 years of obscurity Alexis consulted international and Ukrainian corporates and banks providing strategy and management advisory services. In parallel, he pursued his own research of new energy technologies, eventually focusing on aneutronic fusion by 2014 and coming up with the idea of ultra strong magnetic fields by specialty composite coils by 2016
- To commercialize the idea, Alexis founded Magnite Technologies in 2018

Annex
Theoretical works on hydrogen-boron fusion

Main Author	Published	Title	Publisher
F. Belloni	2018	On the enhancement of p-^{11}B fusion reaction rate in laser-driven plasma by α → p collisional energy transfer	Physics of Plasmas 25, 020701
S. Eliezer	2016	Avalanche proton-boron fusion based on elastic nuclear collisions	Physics of Plasmas 23, 050704
S. Moustaizis	2015	Numerical investigations on a compact magnetic fusion device for studying the effect of external applied magnetic field oscillations on the nuclear burning efficiency of D-T and p-11B fuels	SPIE Proceedings, vol. 9515
H. Hora	2015	Fusion energy using avalanche increased boron reactions for block-ignition by ultrahigh power picosecond laser pulses	Laser and Particle Beams
J.J. Santos	2015	Laser-driven platform for generation and characterization of strong quasi-static magnetic fields	New Journal of Physics
P. Lalousis	2014	Optimized boron fusion with magnetic trapping by laser driven plasma block initiation at nonlinear forced driven ultrahigh acceleration	Laser and Particle Beams, vol. 32, issue 03
H. Hora	2014	Fiber ICAN laser with exawatt-picosecond pulses for fusion without nuclear radiation problems	Laser and Particle Beams, vol. 32, issue 01
S. Fujioka	2013	Kilotesla Magnetic Field due to a Capacitor-Coil Target Driven by High Power Laser	Scientific Reports 3, 1170
H. Hora	2011	Possibility for Gaining Nuclear Energy without Radioactivity from Solid Density Hydrogen Boron Using Lasers with Nonlinear Force Driven Plasma Blocks	Journal of Energy and Power Engineering 5, 718-729
G. Mourou	2011	Modern Laser for High Energy Particle Acceleration: A long term view	ICAN Kick off CS1, Geneva, Switzerland
H. Hora	2008	Twenty times lower ignition threshold for laser driven fusion using collective effects and the inhibition factor	Appl. Phys. Lett. 93, 011101/1-011101/3
J. Badziak	2008	Experiments with skin layer acceleration	Optics Electronics Review 5, 1-12
H. Hora	2002	Effects of picosecond and ns laser pulses for giant ion source	Optics Commun. 207, 333-338
Ch. Scheffel	1997	Analysis of the retrograde hydrogen boron fusion gains at inertial confinement fusion with volume ignition	Laser and Particle Beams 15, 565-574
R. Sauerbrey	1996	Acceleration of femtosecond laser produced plasmas	Physics of Plasmas 3, 4712-4716
D. Strickland	1985	Compression of amplified chirped optical pulses	Optics Commun. 56, 219–221
J. Bobin	1974	Nuclear fusion reactions in fronts propagating in solid DT	Laser Interaction and Related Plasma Phenomena, 4B, 465
T. Weaver	1973	Exotic CTR fuel: Non-thermal effects and laser fusion application	Report UCRL-74938, Lawrence Livermore Laboratory
M. Chu	1972	Thermonuclear reaction waves at high densities	Physics of Fluids 15, 412-422

Annex
Experiments with hydrogen-boron fusion

Main Author	Published	Title	Publisher
L. Giuffrida	2018	New targets for enhancing pB nuclear fusion reaction at the PALS facility	Nuclear Photonics Conference 6 / 2018, Brasov, Romania
C. Labaune	2016	Laser-initiated primary and secondary nuclear reactions in Boron-Nitride	Scientific Reports 6 / 2016, 21202
C. Baccou	2015	CR-39 track detector calibration for H, He, and C ions from 0.1-0.5 MeV up to 5 MeV for laser-induced nuclear fusion product identification	Review of Scientific Instruments 86, 083307
C. Baccou	2015	New scheme to produce aneutronic fusion reactions by laser-accelerated ions	Laser and Particle Beams 33, issue 01
A. Picciotto	2014	Boron-Proton Nuclear-Fusion Enhancement Induced in Boron-Doped Silicon Targets by Low-Contrast Pulsed Laser	Physical Review X 4, 031030
C. Labaune	2013	Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma	Nature Communications 4, 2506
S. Kimura	2009	Comment on "Observation of neutronless fusion reactions in picosecond laser plasmas"	Physical Review E 79, 038401
V. Belyaev	2005	Observation of neutronless fusion reactions in picosecond laser plasmas	Physical Review E 72, 026406

Annex

Copper composites and their properties

Main Author	Published	Title	Publisher
G. J. Wang	2019	Ultrastrong and Stiff Carbon Nanotube/Aluminum−Copper Nanocomposite via Enhancing Friction between Carbon Nanotubes	Nano Lett. 2019, 19, 9, 6255–6262
L. Zheng	2018	N-doped graphene-based copper nanocomposite with ultralow electrical resistivity and high thermal conductivity	Scientific Reports 8 / 2018, 9248
C. Subramaniam	2016	Nano-scale, planar and multi-tiered current pathways from a carbon nanotube-copper composite with high conductivity, ampacity and stability	Nanoscale 8 / 2016, 3888–3894
C. Subramaniam	2013	One hundred fold increase in current carrying capacity in a carbon nanotube–copper composite	Nature Communications 4(2202), 1–7 (2013)

Contacts

📍 8 B Museinyi Lane
Kyiv, Ukraine, 01001

☎ +380 67 441 41 82

✉ info@magnite-tech.com