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Stellarators as a Fast Path to Fusion

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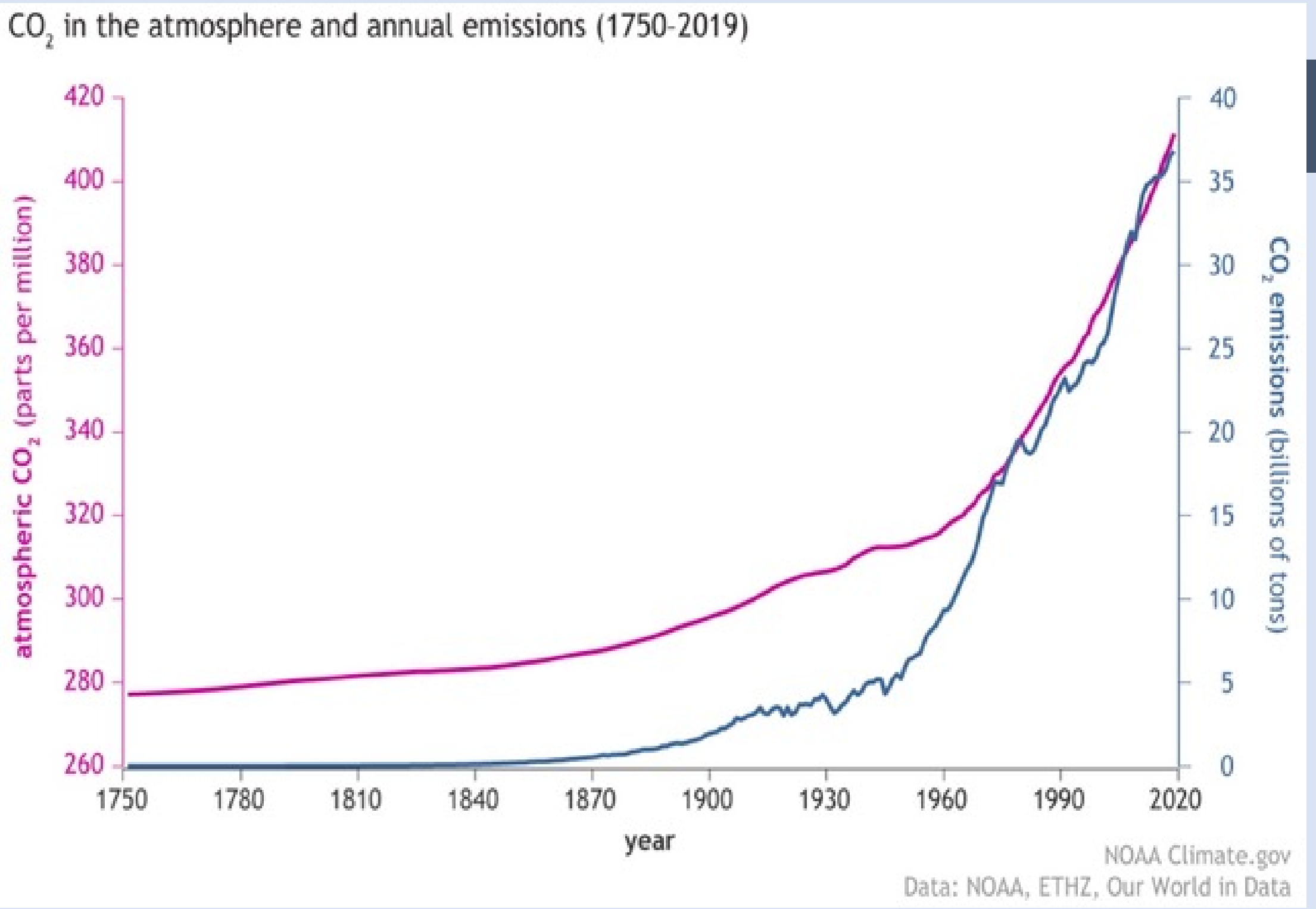
ABSTRACT

- CO2 emissions are doubling every thirty years; a solution must be found within a few doubling times.
- Intermittency, site specificity, waste management, and nuclear proliferation of alternative solutions make fusion attractive.
- The cost of CO_2 emissions is trillions of dollars a year. Can a fusion power plant be constructed within 15 or 20 years at a far lower annual cost?
- Only one concept has empirical evidence of reliable computational design and the robust stability that is required for a fast demonstration of fusion: the stellarator.

CO_2 Problem


CO_2 in the atmosphere and annual emissions (1750-2019)

NOAA Climate.gov
Data: NOAA, ETHZ, Our World in Data

- Two steps to addressing CO_2 problem: (a) development of options and (b) deployment. For fusion, of order 1000 reactors are required to affect CO_2 problems but only one is needed to define the option.
- Minimization of time and risk are far more important than the annual program cost.
- Unlike tokamaks, the magnetic field structure in stellarators is primarily determined by the external coil rather than by the plasma currents.
- This makes computational design reliable and gives robust passive plasma maintenance and stability---needed for fast power plant operation.

Suitability of Stellarators for Fusion

Deuterium-Tritiium Issues require physics changes from tokamak DEMO designs (Abdou et al, NF <61>, 13001 (2021)).

1. An adequate tritium breeding ratio (TBR) is compromised by stabilizing shells and penetrations for current drive. Walls must be too thin to withstand disruptions. These problems are solved by stellarators.
2. Tritium burn fraction benefits from having less than 50% tritium. Fusion reactivity is diminished less than burn fraction is increased.
3. Fueling ratio benefits from designing a stellarator with confinement provided by an outer annulus, so refueling pellets do not have to penetrate deeply.
4. Availability can be enhanced by having an open coil design by use of a ribbon-like helical coil and steady-state power-plant operation.

Plasma Steering, Disruptions, and Runaway Electrons

1. Disruptions and electron runaway must be essentially eliminated before tokamaks power plants are possible.
2. Plasma steering is viewed as a way to avoid tokamak disruptions. Although, plasma steering sounds as safe as driving to work, steering a tokamak more closely resembles driving at high speed through a dense fog on an icy road. (Boozer, N.F. about May 2021 and on arXiv).
3. Even shutting down a burning plasma in ITER without a disruption will take at least 60 s due to the lack of passive stability.

Robust passive stability of stellarators eliminates these problems.

Aspects of Computational Design

Making fusion energy possible

1. Most important example is Nührenberg & Zille's demonstration that stellarators can have power-plant relevant neoclassical transport.
2. Scaling laws for stellarators and tokamaks are similar---both gyro-Bohm. Micro-turbulence can be optimized in stellarators.
3. Unfortunately, problems of axisymmetry (delicate stability, electron runaway, Greenwald density limit) not solved by simulation.
4. The W-7X island divertor, designed in 1996, is working as expected. Having outermost confining surface largely determined by external currents and no Greenwald density limit eases divertor design.

Shortening time to fusion energy relative to extrapolation from one experiment to the next

1. Experiments build in conservatism---even minor changes not possible.
2. Experiments are built and operated over long periods of time.
3. Computational design is many orders of magnitude cheaper than major experiments as well as having a far faster time scale.
4. Extrapolations are dangerous when changing physics regimes (plasma control in ignited versus non-ignited plasmas, formation of beams of relativistic electrons, etc.).

Making fusion energy more attractive

1. Stellarators are not more sensitive to magnetic field errors. They do not suffer from error-field amplification due to current-driven kinks.
2. Control coils can be designed, as on tokamaks, to cancel effect of error fields and to provide flexibility in physics experiments.
3. Curl-free fields can be designed that have excellent confinement properties. Designs are reliable as long as beta is below theoretical limits. In experiments, beta-limits are soft.

Discussion

When ITER was initiated in 1985 by Reagan and Gorbachev

1. The solution (1988) to unacceptable neoclassical transport in stellarators was unknown.
2. The limits on current drive efficiency (1988) and tokamak density (1988) were also unknown.
3. The runaway electron problem (1997) was not appreciated.
4. The urgency of ending doubling of CO_2 emissions was not known.

Costs associated with CO_2 emissions are trillions of dollars a year

1. Necessitate a quick determination of options for solutions.
2. Fusion is attractive because intermittency, site specificity, waste, and nuclear proliferation issues of alternatives.
3. For minimization of time and risk, the stellarator is the obvious fusion option: (a) experimentally-demonstrated computational-design reliability, and (b) no problems requiring inventions.

5\. Tokamaks require an invention to solve disruption and runaway issues before being suitable for a power plant. The stellarator may be that invention.

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