Technical Report: The Polomac approach to fusion energy

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Deutelio is a private initiative promoting an alternative path to fusion energy. The Tokamak research line pursued worldwide since 1970 met several difficulties, heavily jeopardising the objective of fusion energy production before 2050, as a support to the global effort towards Net Zero Emissions. As a result, new plasma magnetic confinement concepts, such as Stellarators or overlooked alternatives like the poloidal confinement are being pursued to achieve more efficiency and better performance.

The Polomac is a poloidal magnetic configuration where the outboard magnetic lines are deviated aside together with the plasma, to open some accesses to the dipole coils located inside the plasma. These accesses, called magnetic tunnels, are used to support, feed and cool the dipole coils. The magnetic tunnels avoid the impact with plasma which led to abandon past poloidal experiments, despite their good stability and confinement efficiency.

The poloidal confinement can achieve Deuterium-Tritium reactor conditions with a magnetic field 3 times weaker than the Tokamak, steady state rather than pulsed. With the same high field as in the Tokamak the poloidal confinement could achieve Deuterium-Deuterium reaction, thus avoiding the development of the breeding blanket to produce the Tritium.

This paper presents the Polomac system and the development strategy of Deutelio through a small prototype focused to tune and assess the magnetic tunnels, finally it describes the possibility of the deuterium-deuterium reaction.

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I. Introduction

Fusion energy powers the whole universe and today the public expects the scientists to master it for producing electricity, whenever required and with the least environmental impact. The research is still far from this goal, despite the enormous financial and human efforts applied worldwide since the first oil crisis in 1973.

The next step ITER, originally an acronymous of International Thermonuclear Experimental Reactor, should demonstrate the scientific feasibility of a stable long lasting fusion reaction of deuterium with tritium (DT) [1]. While ITER relies on the external supply of tritium (T) a future industrial reactor needs to breed its own tritium, through lithium bombarded by the neutrons generated in the DT reaction. The breeding system surrounding the plasma and called blanket must be developed after ITER in a demonstration reactor called DEMO. It should prove the reliability, availability, maintenance and economic efficiency of an industrial plant [2] [3].

The Tokamak uses DT reactions because they can be achieved at lower temperatures and pressures than DD. The Tokamak evidenced experimentally a hard limit in withstanding the plasma pressure, up to 2% of the magnetic pressure [4]. The release of T from lithium is well known, but the development of a reliable breeding system could be very long and expensive.

A proof of the concerns about the Tokamak is the fact that no company building power plants in the world (e.g., General Electric, Westinghouse, Mitsubishi, Hitachi, Sulzer, ABB, Areva, Iberdrola, NCC, Ansaldo, Siemens, AEG) has ever tried to challenge fusion energy, whereas for the airplane development, computer, mobile phone and other success stories the private industries were protagonists and engaged relevant capitals. The complexity of the Tokamaks, the limited efficiency and the poor operation margins limited its use to public research institutions.

Recently, some companies challenged to balance the weakness of the Tokamak with new strong High Temperature Superconductors (HTS) operating at much higher magnetic fields [5] and undersized internal coils in the Spherical Tokamak concept [6,7]. Deutelio [8], rather than inventing more remedials to the Tokamak, proposes to change the magnetic configuration, from toroidal to poloidal [8], because it was efficient in pressure confinement and never suffered instabilities [10]. Its major problem, the support of the coils trapped inside the plasma [11, 12], will be solved with the magnetic tunnels.

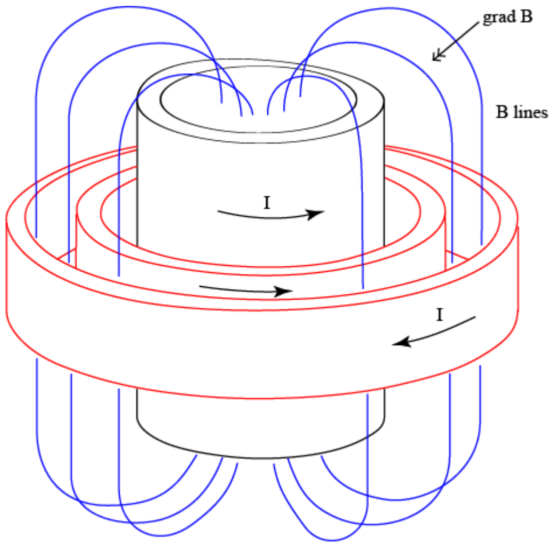

Figure 1: A dipole with the external magnetic lines tightened to the axis by external coils (red). The dipole coil is a solenoid (black)

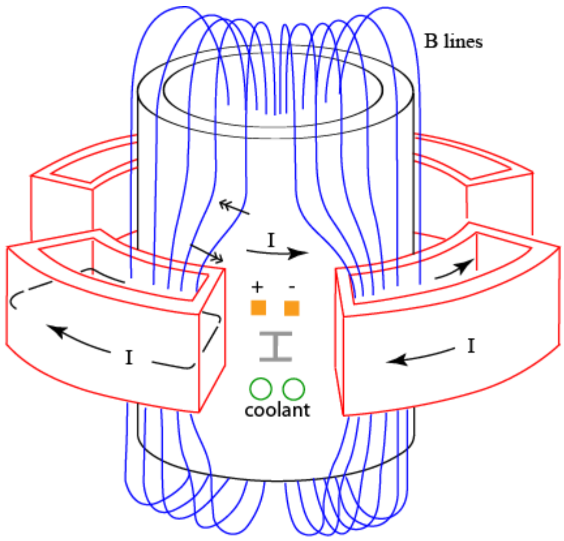

Figure 2: The arrangement of the external coils (red) produces the magnetic tunnels used to feed, to support and to cool the solenoid (black).

II. The Polomac

The Polomac concept originated from a mechanical engineer who, having been involved in the design, construction, and installation of large fusion experiments since 1984, [13-18] decided to resume past research lines abandoned when the Tokamak became the best candidate for a fusion reactor [19, 20].

The goal was to identify a line suitable for market needs (working in a stable and continuous way, able to operate without tritium, affordable to clients) and ready to be built and operated within a reasonable timeframe, helping to meet the global Net Zero Emissions target.

The plasma confinement in the magnetosphere has inspired the idea of the Polomac which is a compact artificial implementation, where active coils replace the ferromagnetic core of the Earth.

The first public announcement of the Polomac was made in 2014, when a paper was published on a peer-reviewed scientific journal [21]. The paper includes a design concept of an experimental plant with a large plasma cross section of a few meters, comparable to the present large Tokamaks. Discussions with experts since 2014 have confirmed the potential of the Polomac and the need to perform an experimental validation, in particular because of the limited cost for the construction of a small rototype.

III. The small prototype

A small prototype has been designed to pursue the development of the Polomac within a private initiative. The central cylinder is 30 cm in diameter and 90 cm high, the external tubular region affected by the tunnel is 3.6 cm thick. Water-cooled copper coils produce 0.2-0.3 T.

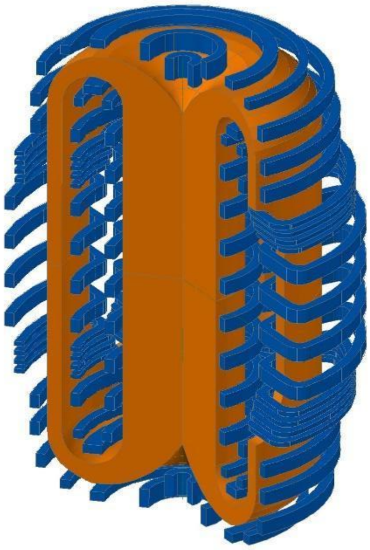

Figure 3: The plasma (orange) surrounded by discrete coils (blue). The right cutting plane is in the midplane of a tunnel, the left one is halfway in between the tunnels.

The plasma is produced inside a 304LN vacuum vessel and it is heated by 5-10 kW of microwaves at electron cyclotron frequency 4 GHz. It should reach a temperature of 100 eV with particle density 10^{20} per cubic meter.

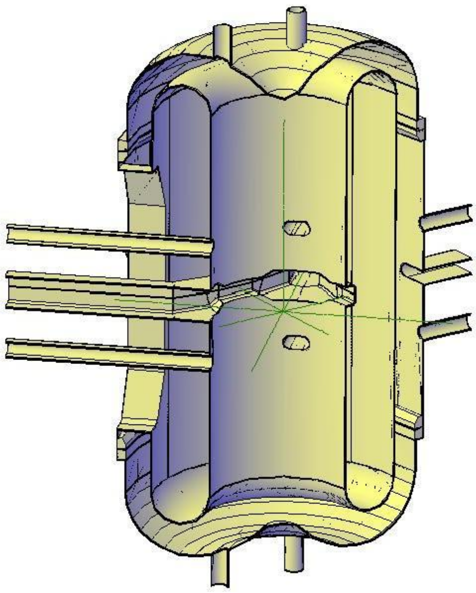

Figure 4: The vessel of the small Polomac prototype.

The internal and external surfaces of the plasma are trimmed by water cooled limiters backed by vacuum pumps. Horizontal and vertical ports are foreseen to target any plasma region.

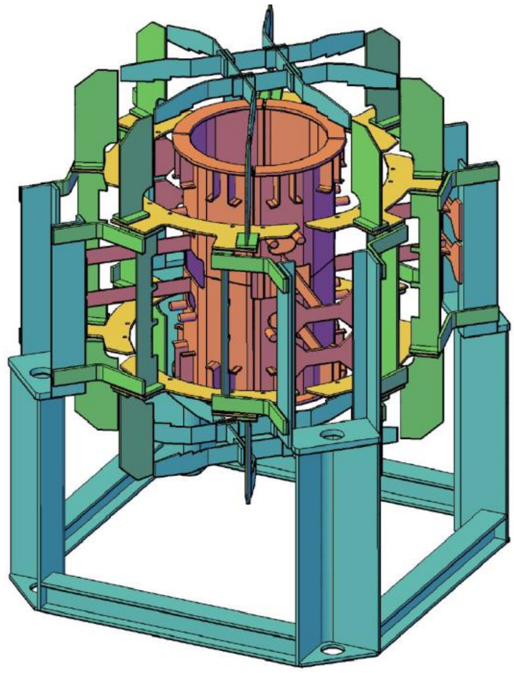

Figure 5: The support structure of the small prototype.

The prototype is aimed only to test and tune the magnetic tunnels and to demonstrate they do not impair the excellent performance of the poloidal magnetic confinement. Plasma physics and technical components are conventional.

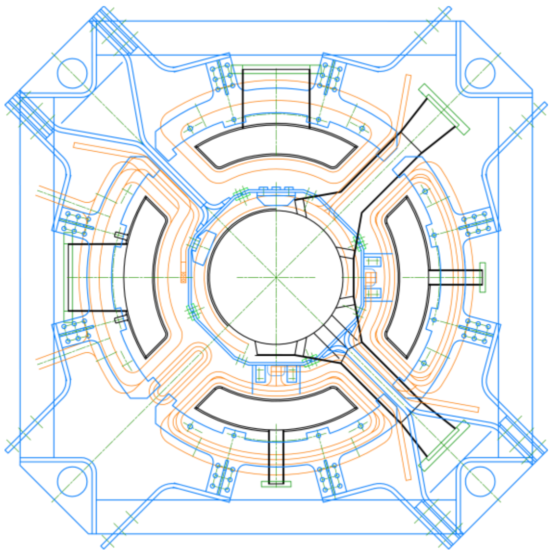

Figure 6: Horizontal midplane cross section of the small Polomac prototype including relevant features located above or below: in blue the support structure, in orange the coils, in black the vessel. Note the central cylinder and the four external channels of the vessel which will be filled by the plasma.

Figure 7: Rendering of the core components: the water cooled copper coils and the vacuum vessel. Height is about 1.2 m, diameter 1m.

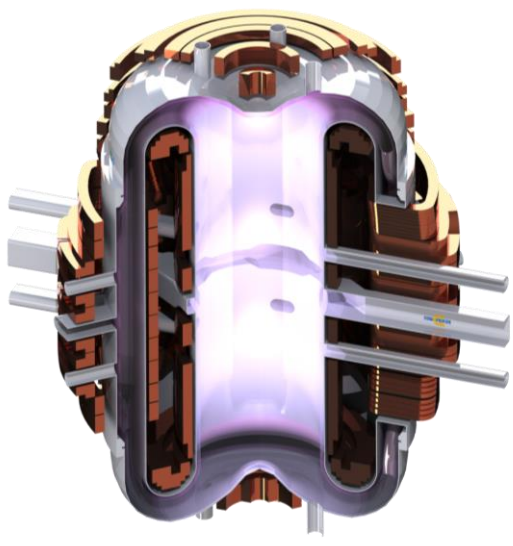

Figure 8: Rendered cut out view of the Polomac prototype. On the right the cut is on the midplane of the tunnel, on the left it is halfway in between.

Features	Value
Plasma volume	150 dm^3
Magnetic field	0.2-0.3 T
Corresponding magnetic pressure	15.9-35.8 kPa
Hydrogen density	up to 10^{20} m^{-3}
Ion temperature	100 eV
Corresponding plasma pressure	1.6-16 kPa
Electron Cyclotron Resonance Heating frequency	2-8 GHz
Electron Cyclotron Resonance Heating power	5-10 kW
Water cooled copper coil highest current	2500 A
Total length of the copper conductors	960 m
Ohmic losses	750 kW
Weight of Ultra High Vacuum Vessel 304L steel	400 Kg

Table 1: Main features and top performance of the small Polomac prototype.

IV. The plasma confinement

The efficiency in plasma confinement of a magnetic configuration is checked by a series of analysis of increasing complexity, such as:

a) Evolution of particle paths starting from different positions with various velocities;
b) Magneto Hydro Dynamic (MHD) analysis of the plasma fluid providing pressure and temperature distributions;
c) Stability of the plasma equilibrium against external magnetic perturbations

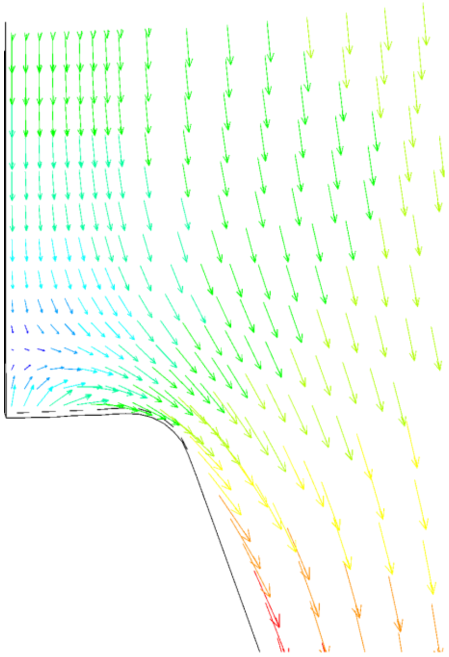

Figure 9: Plot of the magnetic field above the tunnel taken in the middle of the depth. A null point surrounded by a weak magnetic region arises above the vault.

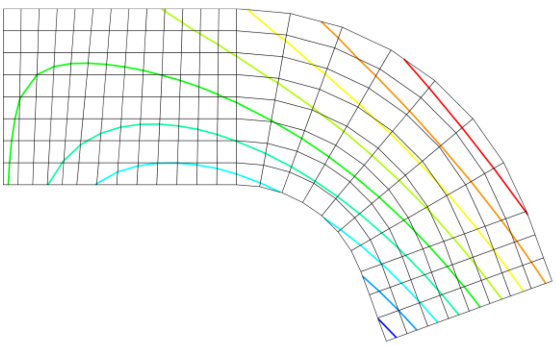

Figure 10: Zoom of the magnetic lines above the tunnel: the lowering flux driving the plasma is pushed on the right by the flux rising from the tunnel.

IV.a) Particle path analysis

Some results of the particle path analysis carried out by Deutelio are shown in the figures below, while a systematic analysis has been contracted to Paul Scherrer Institute, Villlingen, CH.

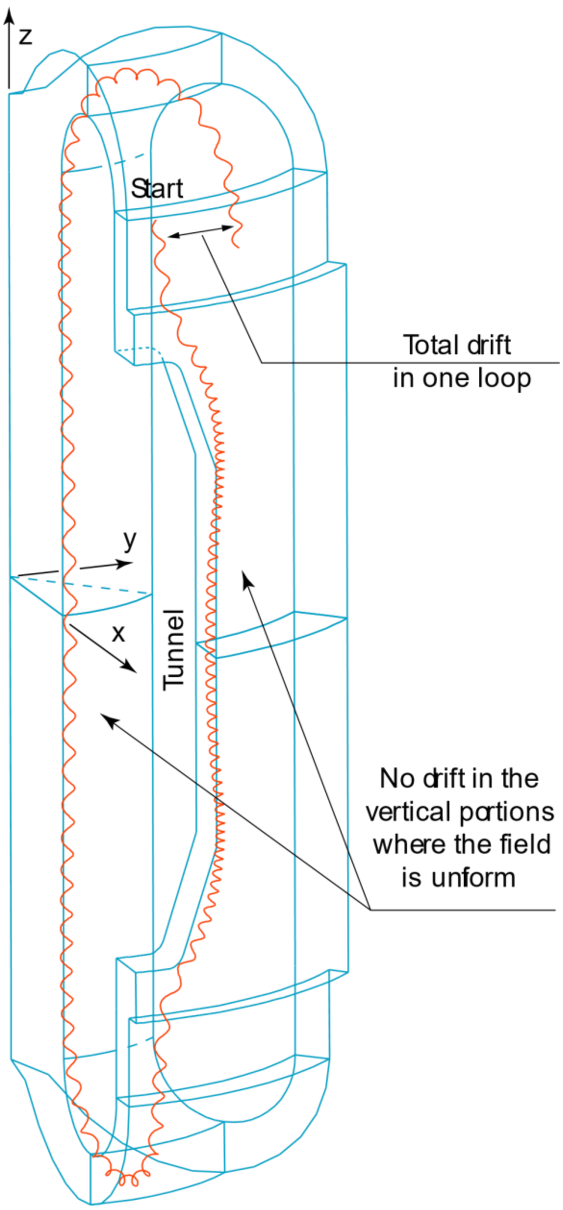

Figure 11: Protons with 100 eV spiralling along the poloidal magnetic lines with azimuthal drifts in the top and bottom domes affected by magnetic gradients.

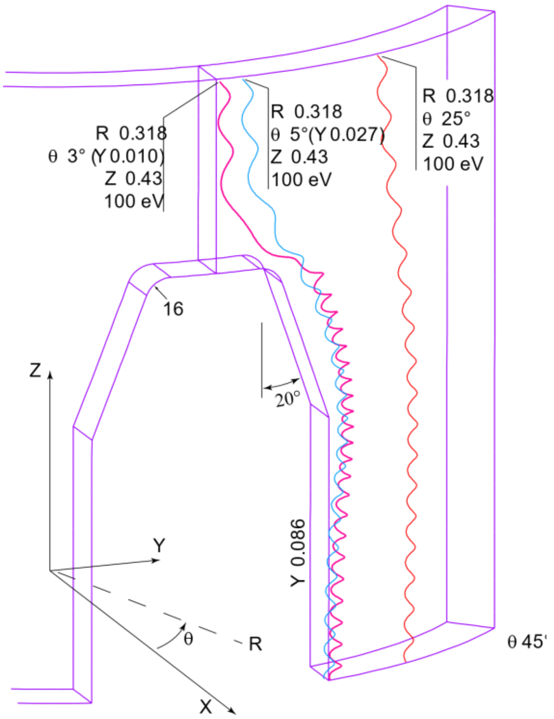

Figure 12: Protons with 100 eV moving aside the tunnel. The spiralling pitch varies with the incidence angle of the velocity to the magnetic field.

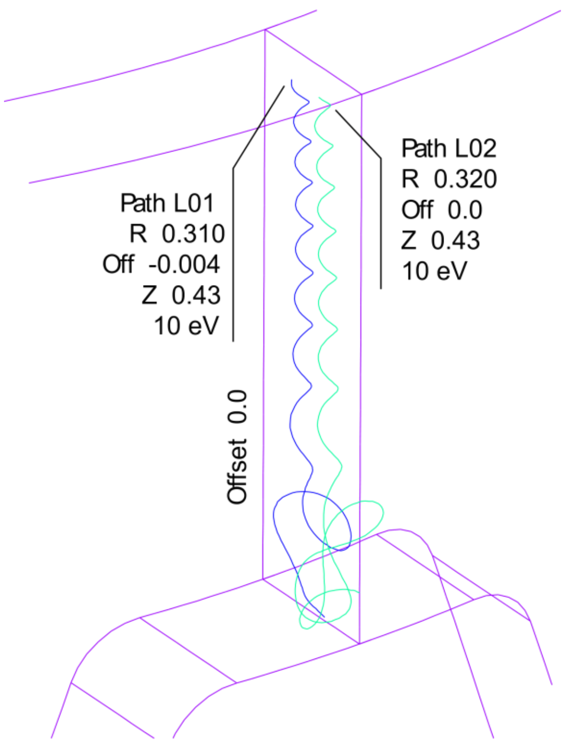

Figure 13: Protons at lower energy 10 eV can be trapped in the weak field region above/below the tunnel and bounce back and forth. They could accumulate drifts or get aligned with the field and escape the confinement.

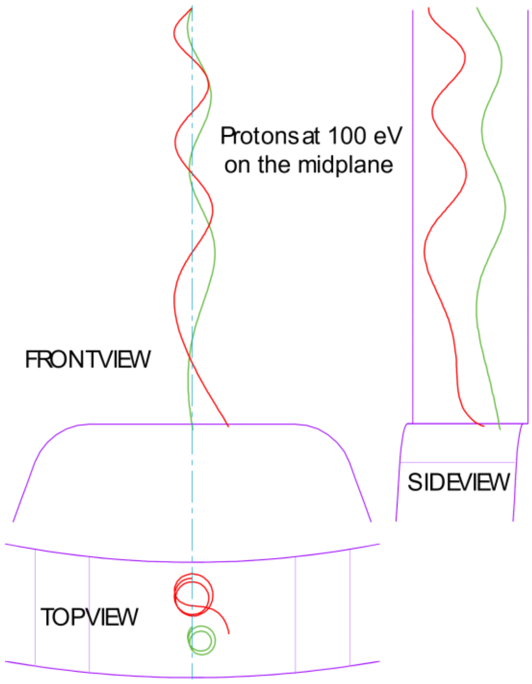

Figure 14: Protons moving straight at 100 eV on the symmetry plane of the tunnel cannot be deviated and hit the vault.

The particles lost on the symmetry plane of the tunnels and in the weak field regions above/below them affect the energy balance of the plasma to an extent which should be quantified with a systematic path analysis and by MHD simulations.

IV.b) MHD analysis

Preliminary MHD analyses of the small Polomac prototype have been carried out by Deutelio, with a custom-made 3D code working in (x,y,z).

Established MHD codes developed for Tokamaks and Stellarators are formulated in toroidal coordinates (x,y,φ), where the solution about the central axis is a Fourier approximation. They are not applicable to the Polomac, because the domain is discontinuous in the azimuthal direction.

The results of the analyses will be cross-checked while the code developed by Deutelio must be validated with benchmarks.

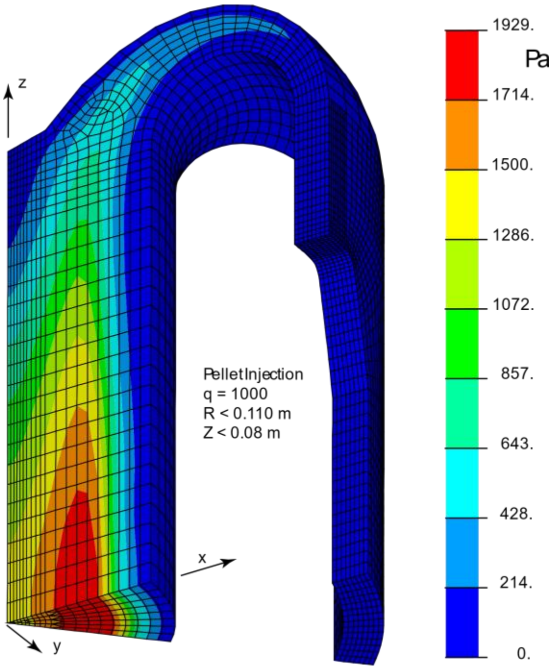

Figure 15: Preliminary results of the pressure distribution by MHD analysis. Higher values are reached in the thick cylinder. Note the void in the central axis suffering a null point and a weak region at the top end.

IV. c) Stability analysis

Stability analysis will be committed to plasma specialists after completing the verification of the above steps. Positive results are expected, because the poloidal system didn't evidence stability issues in the past experiments.

The dipole coils concatenating the magnetic lines probably restrain efficiently any distortion.

V. DT reactor conditions

The steady operation of a fusion reactor is possible when the energy released by the fusing protons is enough to keep the plasma warm at the reaction temperature against external losses.

The fusion power depends on the density of the plasma and the cross section of the nuclear reaction, according to the following formula:

$$P_{fus} = \frac{1}{4} n^2 < \sigma v > E_{DT} \; [\frac{MeV}{m^3}] \qquad (1)$$

Where *n* is the number of particles per cubic meter, <σv> is the cross section of the reaction in cubic meter per second, E_{DT} is the energy 17.6 MeV released by two protons and shared between the resulting α particle (20%) and the neutron (80%).

The share of the kinetic energy is determined by the inverse of the weight ratio.

The cross section of the DT reaction is about:

$$< \sigma v >= 1.1\ 10^{-24}\, T_{keV}^2 \; [\frac{m^3}{s}] \qquad (2)$$

The plasma losses depend on the confinement efficiency, which is measured by the confinement time τ_E. It can be predicted by a physics model or derived from the experiment, by dividing the plasma temperature with the applied heating. Remember that present plasmas are not nuclear and are warmed by external devices like microwaves and neutral beams. Current large Tokamaks reach confinement times τ_E of 0.1-0.4 s, while ITER is predicted to have 4-5 s.

The plasma energy per unit volume is the sum of the particle energy:

$$E_{pl} = 3nT_{eV} \; \left[\frac{eV}{m^3}\right] \qquad (3)$$

The power losses to the wall are then:

$$P_{los} = \frac{E_{pl}}{\tau_E} \; \left[\frac{eV}{s\, m^3}\right] \qquad (4)$$

Fusion should compensate for the plasma losses, but only a fraction of energy 1/5 (20%) released to the α particle remains in the plasma, because the neutrons are insensitive to the magnetic field and escape quickly to the wall without transferring their energy to the plasma.

The energy balance (4) compiled with the references (1) and (2) and a factor 1/5 sets the following burning condition for a reactor.

$$\frac{1}{4} n^2 1.1 10^{-24} T_{keV}^2 17.6 MeV\, \frac{1}{5} \geq 3nT_{eV} / \tau_E \qquad (5)$$

It is easily reduced into the simpler form:

$$n_{20} T_{keV} \tau_E \geq 31 \qquad (6)$$

which is known as the Lawson criterion.

ITER is expected to meet (6) at plasma density 10^{20}, ion temperature 8.1 keV and confinement time 4-5 s.

Similar conditions can be achieved by a Polomac with half magnetic field, i.e. 2-3 T rather than 5.3 T owing to the higher confinement efficiency of the poloidal configuration.

VI. DD reactor conditions

The reactor conditions for DD can be derived similarly to the DT case, but the cross section is about 100 times lower and the fusion energy is different. The DT reaction evolves into two branches with equal probability. The energy released to the plasma is the average of their contributions.

$$D + D = He^3 + n + 3.7\ MeV \qquad (7)$$

$$D + D = T + H + 4.03\ MeV \qquad (8)$$

In the first reaction (7) the energy of the ionised particles remaining inside the plasma is 25% while in the second reaction (8) all products are ionised and release their energy to the plasma. Since both branches have the same probability the fusion energy available in the ionised particles to compensate the plasma losses is:

$$E^+_{DD} = \frac{1}{2}4.03\ MeV + \frac{1}{2}3.7MeV\frac{1}{4} = 2.48\ MeV \qquad (9)$$

This value is lower than the energy released to ionised particles of the DT reaction:

$$E^+_{DT} = \frac{1}{5}17.6\ MeV = 3.52\ MeV \qquad (10)$$

The burning condition for a DD reactor is then:

$$\frac{1}{4}n^2 1.110^{-26} T^2_{keV} 2.48MeV \geq 3nT_{ev}/\tau_E \qquad (11)$$

which is easily rewritten in the simpler form:

$$n_{20}T_{keV}\tau_E \geq 4399 \qquad (12)$$

evidencing a difference factor 142 over the DT reactor condition (6).

This factor results from the combination of the lower cross section of DD with the minor energy contribution than DT.

The DD operation is precluded to the Tokamak given the performance limits, while a Polomac could achieve higher temperatures 100-200 keV, a higher density about 10^{21} and energy confinement time 20-40 s.

VII. Polomac evolution

The possibility to operate in steady state with DD pushes to resume and develop the poloidal magnetic confinement using the Polomac scheme.

Development and demonstration of the magnetic tunnels can be done by operating the small prototype working with hydrogen (H). The lack of relevant radiation allows human access for quick adjustments and tuning. Deutelio expects to build the small prototype in 1 year and to complete the experimental activity in the next 2-3 years.

The know-how gained on the magnetic tunnels will allow the design of the first fusion reactor which will need a thick radiation shield. It will be a low temperature 150-200° C heat generation unit for industrial applications, food processing, sport facilities and district heating,

An advanced model operating at higher temperature 350°C with improved reliability will come later for the production of electricity, also combined with heat.

Market research identified direct applications of the small Polomac prototype to test and calibrate plasma diagnostics, to produce X-rays and XUV, to test aerospace parts in challenging plasma conditions, as ion source for other devices.

Other applications of the future reactor could be neutron production, tritium production, laser-plasma particle acceleration.

Typical adopters will be medium-to large research and industrial laboratories in applied plasma physics, nuclear fission, nuclear fusion, aerospace technology.

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