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FRC collider

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Abstract. A method for the formation of a compact torus (CT or FRC) – a closed current loop in plasma – using an inductive energy storage device is proposed. This method has shown a high efficiency of magnetic energy conversion of the accumulator. Two compact tori accelerated towards each other, at the point of collision, gave a plasma temperature of more than 1 keV and a duration of soft X-ray radiation of about one microsecond, which is three orders of magnitude longer than the duration of such radiation at the Z-machine facility, USA.
Keyword: compact torus, inductive energy storage, soft X-rays.

1. Introduction

Compact torus is an axisymmetric configuration with a closed current loop in plasma, or FRC – Field Reversed Configuration, shown in Fig.1.

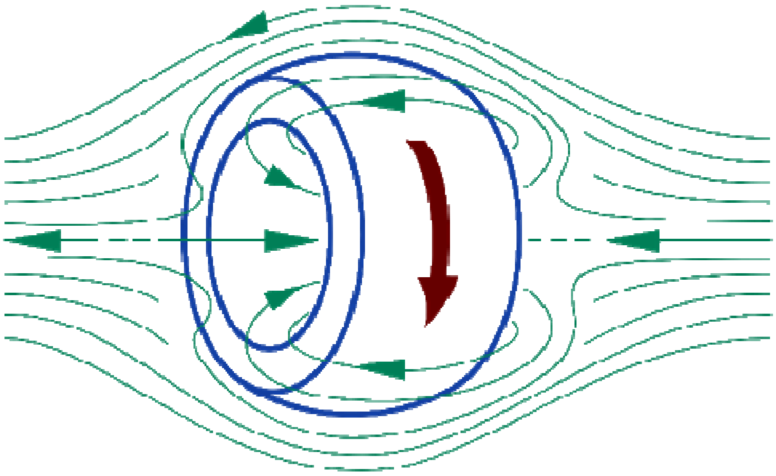

Fig.1. FRC – Field Reversed Configuration.

The main advantage of FRC is the possibility of their acceleration and compression by an external magnetic field for use in inertial thermonuclear fusion, as well as in electric rocket thruster or for collective ion acceleration. For these purposes, a plasma flow velocity of the order of 1000 km/sec (10 keV for deuterium) and its mass of the order of micrograms are required. To achieve such speeds, multiple acceleration of the FRC is necessary. The physical principle of acceleration is based on Ampère's law of repulsion/attraction of conductors with current. The main idea of such colliders on compact tori is the formation of two FRC with their subsequent acceleration towards each other and their collision [1]. Compact tori were obtained using theta pinches at the Novosibirsk Institute of Nuclear Physics, later at TRINITI, the Sukhum Physicotechnical Institute, and in the USA at the Naval Research Laboratory (NRL), Los Alamos. The works [2, 3] present the results of research in this area. Now two private US companies Tri Alpha Energy (tae.com, rised more than $1 billion, of which 50 million from Rusnano) and Helion Energy (helionenergy.com, received $500 million in 2021) are conducting research on controlled fusion using FRC (Fig.2 and Fig.3).

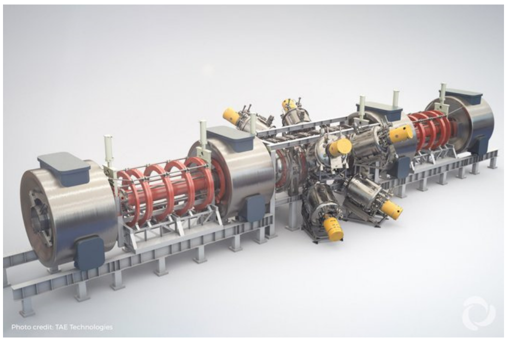

Fig.2. Device NORMAN Tri Alpha Energy.

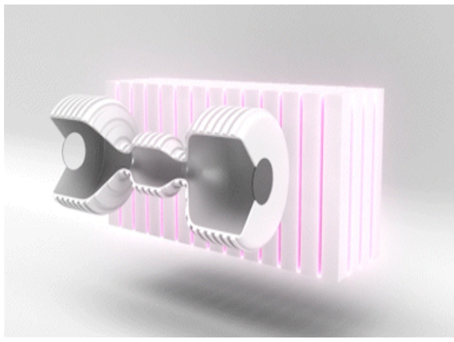

Fig.3. Helion Energy device, length 20 m.

The latter even promises to feed power into the grid in 2024 (according to a tweet by Sam Altman, the main investor, Elon Musk's Open AI partner). I met Tri Alpha Energy co-founder Norman Rostoker in 1998 with only the initial idea of a current cut. TAE has now moved to magnetic plasma confinement at FRC. The standard method of forming FRC is induction, of the theta-pinch type, when a high-voltage low-inductance capacitor bank is discharged into a one-two turn winding in a chamber with a working gas (usually deuterium) and with a plasma previously created there. This method is not efficient – the current in a compact torus is always small. We have proposed a new method for the formation of compact tori in inductive storage.

2. Description of the method and experiments

The method was based on three ideas, the description of which is given below. The first idea was as follows – it is necessary to accumulate magnetic energy in an inductive storage device in the form of a solenoid, covering the vacuum working chamber. Before the current maximum, create plasma in this volume and cut off the current; but the circuit worked poorly – the captured magnetic flux was small [4]. Physically, this can be explained as follows. If we talk about an axisymmetric system like a solenoid, then we need to excite a closed current in the plasma with the direction of electron movement across the magnetic field line of the solenoid. This is always bad, because. plasma conductivity is not enough. The second idea just made it possible to solve this problem – in the chamber, before the current was interrupted, the injected plasma was additionally heated by longitudinal currents from a separate capacitor bank through the plasma along the inner surface of the solenoid, and the return conductors were located outside, symmetrically along the perimeter. As a chamber, industrially manufactured cylinders based on epoxy resins with a filler were used; windings of powerful industrial transformers are wound on such cylinders; they are significantly cheaper than Pyrex glass chambers. The effect was significant – the level of the captured flow exceeded 70%. Compression began to appear and the magnetic field intensified in the center of the chamber [5]. The third idea – it was decided to abandon the inductive storage in the form of a solenoid and switch to a flat inductance in the form of an Archimedes spiral.

The technology of forming a flat inductive store with filling its conductors with artificial resins with fillers was worked out, but nevertheless, shock loads on current-carrying turns sometimes cause depressurization of such flanges. The inductive storage also served as the end flange of the cylindrical vacuum chamber; the installation scheme is shown in Fig.4. Four independent capacitor banks and arresters were used (a total of 32 capacitors, K-5-40, charging voltage 20–26 kV, energy storage up to 60 kJ). Another small battery was used for plasma injection along the vacuum side of the storage. The chamber was under direct evacuation with a diffusion pump, pressure $5\cdot10^{-3}$ mm Hg. The interruption of the current was always carried out with the help of exploding wires, the number of which was selected experimentally to interrupt the current near its maximum and the wires themselves were covered with sand. This reduced the noise and shortened the current interruption time. To measure currents and magnetic fields, Rogowski coils, single loops on the chamber and small sensors (20 turns coils with a diameter of 8 mm) were used, mounted on the axis of the chamber in vacuum. The sensors actually measure a voltage proportional to the voltage applied to the inductive storage, this is equivalent to measuring the voltages on the primary and secondary windings of a transformer with different coupling coefficients between them. To obtain a current signal, these voltages are integrated by RC circuits.

Without plasma, the integrated signals from the magnetic field sensors always coincide in shape with the current signals of the inductive storage. After a complete interruption of the current in the storage circuit, these signals are already caused by the current in the plasma, and it is easy to fix the level of the captured magnetic flux of the inductive storage from them. Typical signals are shown in Fig.5 and Fig.6.

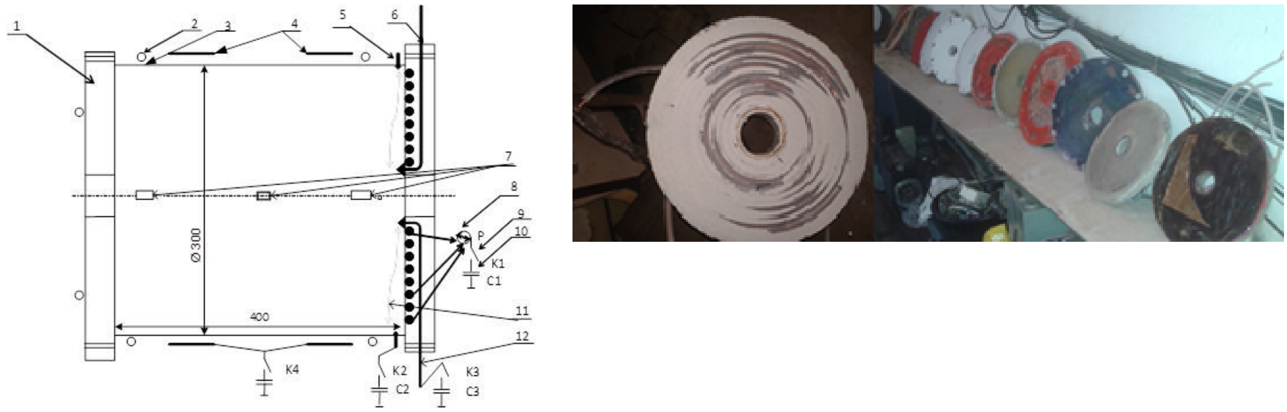

Fig.4. Scheme of the experimental setup and photo of inductive storage: 1 – plexiglass flange, 2 – measuring loop, 3 – dielectric chamber housing, 4 – compression coils, 5 – plasma guns (12 pcs.), 6 – flange with inductive storage, 7 – magnetic field sensors, 8 – current interrupter, 9 – switches to capacitor banks (one switch for each of 4 batteries), 10 – capacitor bank, 11 – turns of inductive storage, 12 – high-voltage input from the battery for plasma preheating.

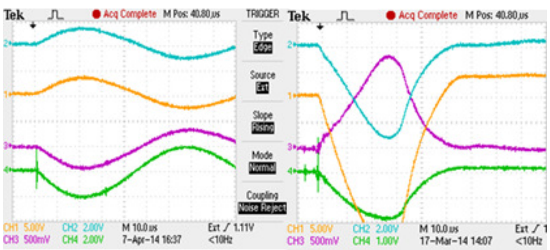

Fig.5. Typical oscillograms of current and magnetic fields of an inductive storage.

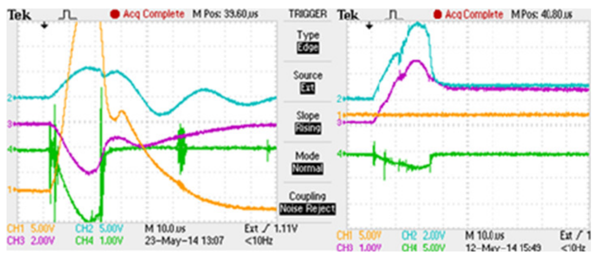

Fig.6. Oscillograms of current and magnetic fields during the formation of FRC in plasma.

Green – current in the inductive storage without forced break and with break, both cases without plasma. Blue, yellow, pink – magnetic fields, the magnetic field repeats the shape of the current. Made in different experiments, so the direction of the magnetic field signals depends on the connection of the two sensor outputs. With a break in the current and with plasma – the capture of the magnetic flux is visible, the trailing edge at the current becomes short. Sometimes the magnetic field signals are unusually long, they are rare and indicate the formation of a spheromak configuration with a toroidal current. Before the current break near its maximum, the plasma is injected along the "vacuum" surface of the accumulator with the help of 12 plasma guns located on a large diameter. Plasma heating is carried out by a radial current from the electrodes at the center of the flange to the electrodes at the periphery, as is done in installations with a plasma focus. When the current is interrupted, a closed current loop appears in the plasma, capturing most of the magnetic flux of the inductive storage and retaining the energy stored in the magnetic field, and the radial current for heating also repels the emerging compact torus from the flange. The current in the additional external compression winding can keep the coil with current in the plasma from expanding along the radius and accelerate it. Typical oscillograms are shown in Fig.7. It can be seen that after the interruption of the current, most of the magnetic flux is preserved. The current in the FRC was estimated to reach several tens of kiloamperes with a diameter of up to 30 cm. The velocity of the plasma CT, measured by the delay in the appearance of the signal from the loop on the opposite side of the chamber, was 40 km/s.

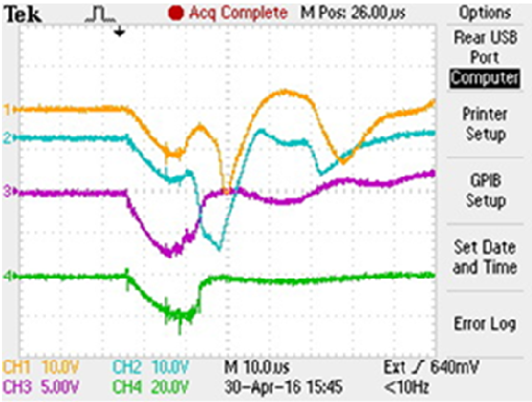

Fig.7. Oscillograms of current and magnetic fields in the CT acceleration mode.

Fig.8 You can see the location of 20 plasma guns on the outer diameter of the Helion Energy setup and formed with theta-pinch FRC in the center.

Green – current in the inductive storage, pink – magnetic field from the sensor on the camera axis near the storage, CT repels from the storage and the signal drops, blue – magnetic field from the sensor on the camera axis in its center, a large level of magnetic field capture and its growth from the approaching compact torus is visible. Yellow – magnetic field from the loop on the opposite flange. The maximum occurs in a few microseconds from the signal maximum in the center. In the collider, it is necessary to form two FRC with the same current direction so that they are attracted to each other. The scheme of the experiment is shown in Fig.9.

They were carried out in the same chamber with a diameter of 300 mm and a length of 400 mm. Two inductive storage and seven independent capacitor banks and switches were already used (60 capacitors in total, K-5-40, charging voltage 20–26 kV, energy reserve up to 100 kJ), all other conditions remained the same. When two FRC collide, their magnetic field lines reconnect, which is accompanied by plasma heating and a flash of soft X-ray radiation with a duration of up to 1 µs. For registration, a diamond semiconductor detector (PPD-PCD) [5] with an Al filter 5 µm thick was used, and the pulse of "all" radiation, starting from visible light, was well felt by the MP-38 transistor crystal. The duration of such radiation turned out to be about 15 µs. And it always started a few microseconds after the current in the inductive storages was interrupted. Typical oscillograms are shown in Fig.10. Photos of the PCD detector and the exposed Image Plate are shown in Fig.11. Soft x-rays indicate a temperature above 1 keV, and its duration is three orders of magnitude higher than on the Z-machine (USA). The magnetic field from the compression turns no longer penetrates into the closed current loop, which also indicates a keV temperature. Modeling of processes in CT is given in the dissertation [7] and at present there is an urgent need to continue such work.

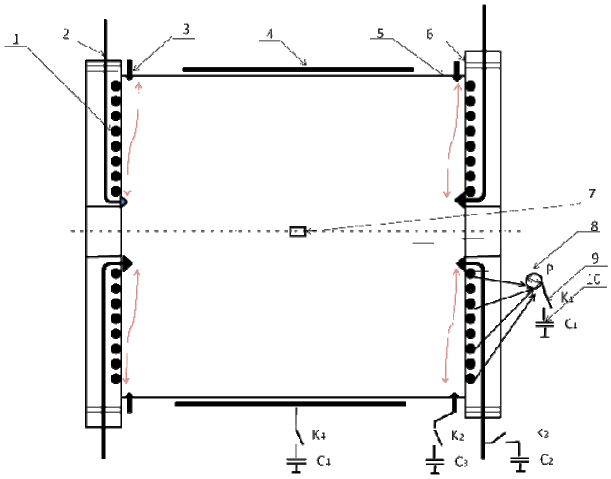

Fig.9. Scheme of setup for collision of two FRC: *1* – inductive storage in the form of a 3-start spiral (to reduce the total inductance and reduce the rise time of the current in the inductive storage), *2* – high-voltage electrodes for plasma heating, *3* – plasma guns (12 pieces), *4* – a coil for radial plasma compression, *5* – a vacuum chamber with a diameter of 300 mm, *6* – end flanges with inductive storage devices filled with artificial resins with fillers (for strength), *7* – magnetic field sensor in the center of the chamber (one of three is shown), *8* – current interrupter on exploding wires, 9 – switches K1–K8 (half is shown), *10* – capacitor banks C1–C8 (half is shown).

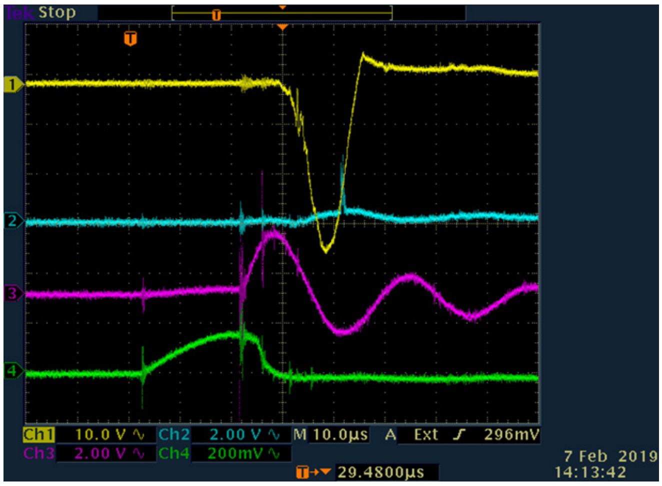

Fig.10. Oscillograms of inductive storage currents, current for plasma heating and signals from radiation detectors *1* – yellow – "total" radiation pulse from the MP-38 transistor crystal, *2* – blue – soft X-ray pulse from a diamond detector, *3* – pink – plasma heating current, 4 – green – current through the inductive storage.

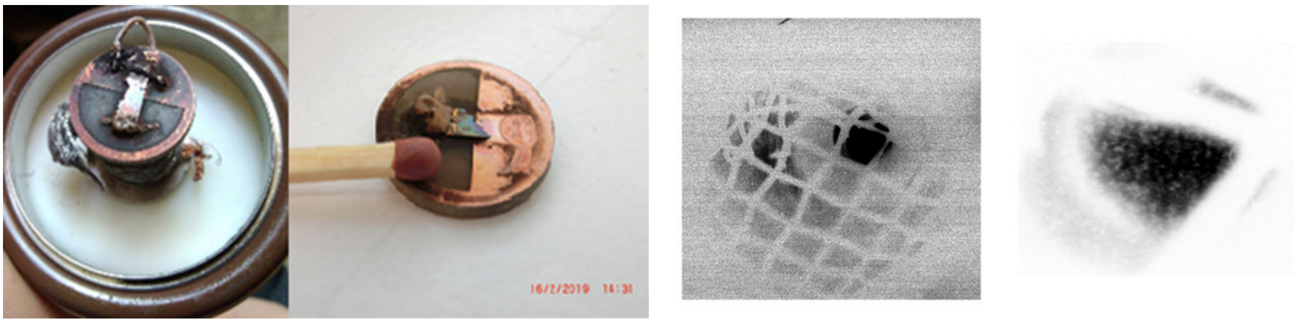

Fig.11. The diamond crystal of the PCD soft X-ray detector after the experiment is sometimes destroyed due to the high radiation power and the soft X-ray radiation from the camera, taken on an Image Plate (light-insensitive plastic), through an 8 mm hole with a metal mesh.

3. Conclusion

Electric rocket engines. When accelerating a compact torus, the same force acts on the coils with current on the chamber. With a current in a closed loop (torus) of 100 kA and in multi-turn windings of the order of 10 kA×N×turns with a diameter of several meters, the force will reach hundreds of kilonewtons, while existing electric rocket engines give thrust no more than a few newtons at 100 kW consumption. In the frequency mode, the switched power will reach the megawatt range, which will be one of the difficult tasks for the next generations of researchers, along with the need to use superconductors. And finally, several EJEs with tons of thrust are the real protection of the Earth from asteroids! The method of formation of QDs and their collider is also suitable for other fusion reactions: D-3He, unneutron boron proton with the release of three charged alpha particles, and the use of two electrodes at the meeting point of FRC can lead to direct conversion of the released energy into electrical energy.

Acknowledgements

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4. References

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