

SYSTEMS AND METHODS FOR MERGING AND COMPRESSING COMPACT TORI

FIELD

[0001] The embodiments described herein relate generally to pulsed plasma systems and, more particularly, to systems and methods that facilitate merging and compressing compact tori with superior stability as well as significantly reduced losses and increased efficiency.

BACKGROUND INFORMATION

[0002] The Field Reversed Configuration (FRC) belongs to the class of magnetic plasma confinement topologies known as compact toroids. It exhibits predominantly poloidal magnetic fields and possesses zero or small self-generated toroidal fields (see M. Tuszewski, Nucl. Fusion **28**, 2033 (1988)). The attractions of such a configuration are its simple geometry for ease of construction and maintenance, a natural unrestricted divertor for facilitating energy extraction and ash removal, and very high average (or external) β (β is the ratio of the average plasma pressure to the average magnetic field pressure inside the FRC), *i.e.*, high power density. The β metric is also a very good measure of magnetic efficiency. A high average β value, *e.g.* close to 1, represents efficient use of the deployed magnetic energy and is henceforth essential for the most economic operation. High average β is also critically enabling the use of aneutronic fuels such as D-He³ and p-B¹¹.

[0003] The traditional method of forming an FRC uses the field-reversed θ -pinch technology, producing hot, high-density plasmas (see A. L. Hoffman and J. T. Slough, Nucl. Fusion **33**, 27 (1993)). A variation on this is the *translation-trapping* method in which the plasma created in a theta-pinch “source” is more-or-less immediately ejected out of the formation region and into a confinement chamber. The translating plasmoid is then trapped between two strong mirrors at the ends of the confinement chamber (see, for instance, H. Himura, S. Okada, S. Sugimoto, and S. Goto, Phys. Plasmas **2**, 191 (1995)). Once in the confinement chamber, various heating and current drive methods may be applied such as beam injection (neutral or neutralized), rotating magnetic fields, RF or ohmic heating, etc. This separation of source and confinement functions offers key engineering advantages for potential future fusion reactors. FRCs have proved to be extremely robust, resilient to dynamic formation, translation, and violent capture events. Moreover, they show a tendency to assume a preferred plasma state (see *e.g.* H. Y. Guo, A. L. Hoffman, K. E. Miller, and L. C. Steinhauer, Phys. Rev. Lett. **92**, 245001 (2004)). Significant progress has been made in the last decade developing other FRC formation methods: merging spheromaks with oppositely-directed

helicities (see e.g. Y. Ono, M. Inomoto, Y. Ueda, T. Matsuyama, and T. Okazaki, Nucl. Fusion **39**, 2001 (1999)) and by driving current with rotating magnetic fields (RMF) (see e.g. I. R. Jones, Phys. Plasmas **6**, 1950 (1999)), which also provides additional stability.

[0004] FRCs consist of a torus of closed field lines inside a separatrix, and of an annular edge layer on the open field lines just outside the separatrix. The edge layer coalesces into jets beyond the FRC length, providing a natural divertor. The FRC topology coincides with that of a Field-Reversed-Mirror plasma. However, a significant difference is that the FRC plasma can have an internal β of about 10. The inherent low internal magnetic field provides for a certain indigenous kinetic particle population, i.e. particles with large larmor radii, comparable to the FRC minor radius. It is these strong kinetic effects that appear to at least partially contribute to the gross stability of past and present FRCs, such as those produced in the recent collision-merging experiments.

[0005] The *collision-merging* technique, proposed long ago (see e.g. D. R. Wells, Phys. Fluids **9**, 1010 (1966)) has been significantly developed further: two separate theta-pinches at opposite ends of a confinement chamber simultaneously generate *two* plasmoids (e.g., two compact tori) and accelerate the plasmoids toward each other at high speed; they then collide at the center of the confinement chamber and merge to form a compound FRC. In the construction and successful operation of one of the largest FRC experiments to date, the conventional collision-merging method was shown to produce stable, long-lived, high-flux, high temperature FRCs (see e.g. M. Binderbauer, H.Y. Guo, M. Tuszewski *et al.*, Phys. Rev. Lett. **105**, 045003 (2010), which is incorporated herein by reference). In a related experiment, the same team of researchers combined the collision-merging technique with simultaneous axial acceleration and radial compression to produce a high density transient plasma in a central compression chamber (see V. Bystritskii, M. Anderson, M. Binderbauer *et al.*, Paper P1-1, IEEE PPPS 2013, San Francisco, CA. (hereinafter “Bystritskii”), which is incorporated herein by reference). This latter experiment reported in Bystritskii utilized a multitude of acceleration and compression stages before final collisional merging and represents a precursor concept to the system subject to this patent application.

[0006] In contrast to the embodiments described here, the precursor system described in Bystritskii featured simultaneous compression and acceleration of compact tori within the same stage by using active fast magnetic coils. Five such stages were deployed on either side of a central compression chamber before magnetically compressing the merged compact tori. While the precursor experiment achieved respectable performance, it exhibited the following deficiencies: (1) Simultaneous compression and acceleration led to inefficient use of driver energy deployed for magnetic compression due to a timing mismatch; (2) Temperature and density decreased as plasma expanded

during transit between sections; (3) Abrupt transitions between adjacent sections led to large losses due to plasma-wall contact and generation of shockwaves.

[0007] Aside from the fundamental challenge of stability, pulsed fusion concepts in the medium density regime will have to address adequate transport timescales, efficient drivers, rep-rate capability and appropriate final target conditions. While the precursor system has successfully achieved stable single discharges at encouraging target conditions, the collective losses between formation and final target parameters (presently about 90% of the energy, flux, and particles) as well as the coupling efficiency between driver and plasma (at present around 10-15%) need to be substantially improved.

[0008] In light of the foregoing, it is, therefore, desirable to provide improved systems and methods for pulsed fusion concepts that facilitate a significant reduction of translation and compression losses and an increase in driver efficiency.

SUMMARY

[0009] The present embodiments provided herein are directed to systems and methods that facilitate merging and compressing compact tori with superior stability as well as a significant reduction of translation and compression losses and an increase in coupling efficiency between drivers and plasma. Such systems and methods provide a pathway to a whole variety of applications including compact neutron sources (for medical isotope production, nuclear waste remediation, materials research, neutron radiography and tomography), compact photon sources (for chemical production and processing), mass separation and enrichment systems, and reactor cores for fusion for the future generation of energy and for fusion propulsion systems.

[0010] The systems and methods described herein are based on the application of successive, axially symmetric acceleration and adiabatic compression stages to accelerate and heat two compact tori towards each other and ultimately collide and fast magnetically compress the compact tori within a central compression chamber.

[0011] In certain embodiments, a system for merging and compressing compact tori comprises a staged symmetric sequence of compact tori formation, axial acceleration by fast active magnetic coils, passive adiabatic compression by way of a conically constricting flux conserver, and ultimately merging of the compact tori and final fast magnetic compression in a central compression chamber. The intermediate steps of sufficient axial acceleration followed by adiabatic compression can be repeated multiple times to achieve adequate target conditions before merging and final compression. In this way a reactor can be realized by adding further sections to the system.

[0012] The formation and accelerations stages or sections and the central compression chamber are preferably cylindrically shaped with walls formed of non-conducting or insulating material such as, e.g., a ceramic. The compressions stages or sections are preferably trunco-conically shaped with walls formed from conducting material such as, e.g., a metal.

[0013] Aside from a magnetic bias field (DC guide field) supplied by slow coils, the formation sections, the acceleration sections, and the compression chamber include modular pulsed power systems that drive fast active magnetic coils. The pulsed power systems enable compact tori to be formed in-situ within the formation sections and accelerated and injected (=static formation) into the first compression sections, accelerated in the acceleration sections and injected into the next compression sections, and so on, and then be magnetically compressed in the compression chamber. The slow or DC magnetic coil systems located throughout and along the axis of the system provide an axial magnetic guide field to center the compact tori appropriately as it translates through the section toward the mid-plane of the central compression chamber.

[0014] Alternatively, the modular pulsed power systems of the formation sections can also drive the fast active magnetic coils in a way such that compact tori are formed and accelerated simultaneously (=dynamic formation).

[0015] The systems and methods described herein deploy FRCs, amongst the highest beta plasmas known in magnetic confinement, to provide the starting configuration. Further passive and active compression builds on this highly efficient magnetic topology. The process of using axial acceleration via active fast magnet sections followed by adiabatic compression in simple flux conserving conic sections provides for the most efficient transfer of energy with the least complex pulsed power circuitry. Furthermore, these basic building blocks can be sequenced to take additional advantage of the inherently favorable compressional scaling, i.e. $\Delta p \propto R^4$.

[0016] In another embodiment, the system is configured to deploy spheromaks instead of FRC starter plasmas.

[0017] In another embodiment, the system comprises a staged asymmetric sequence from a single side of the central compression chamber comprising compact tori formation, axial acceleration by fast active magnetic coils, passive adiabatic compression by way of a conically constricting flux conserver, and ultimately merging of the compact tori and final fast magnetic compression in the central compression chamber. Such an asymmetric system would include a mirror or bounce cone positioned adjacent the other side of the central compression.

[0018] In yet another embodiment, the system comprises a thin cylindrical shell or liner comprised of conductive material such as, e.g., a metal, for fast liner compression within the central compression chamber.

[0019] Other systems, methods, features and advantages of the example embodiments will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description.

BRIEF DESCRIPTION OF THE FIGURES

[0020] The accompanying drawings, which are included as part of the present specification, illustrate the presently preferred embodiment and, together with the general description given above and the detailed description of the preferred embodiment given below, serve to explain and teach the principles of the present invention.

[0021] **Figure 1** illustrates a basic layout of a system for forming, accelerating, adiabatically compressing, merging and finally magnetically compressing compact tori.

[0022] **Figure 2** illustrates a schematic of the components of a pulsed power system for the formation and acceleration sections.

[0023] **Figure 3** illustrates an isometric view of an individual pulsed power formation and acceleration skid.

[0024] **Figure 4** illustrates an isometric view of a formation and acceleration tube assembly.

[0025] **Figure 5** illustrates a basic layout of an alternate embodiment of an asymmetric system for forming, accelerating, adiabatically compressing, merging and finally magnetically compressing compact tori.

[0026] **Figure 6** illustrates a detailed view of the system shown in Figure 1 modified to include a shell or liner positioned within the central compression chamber for fast liner compression within the central compression chamber.

[0027] It should be noted that the figures are not necessarily drawn to scale and that elements of similar structures or functions are generally represented by like reference numerals for illustrative purposes throughout the figures. It also should be noted that the figures are only intended to facilitate the description of the various embodiments described herein. The figures do not necessarily describe every aspect of the teachings disclosed herein and do not limit the scope of the claims.

DESCRIPTION

[0028] The present embodiments provided herein are directed to systems and methods that facilitate merging and compressing compact tori with superior stability as well as a significant reduction of translation and compression losses and an increase in coupling efficiency between drivers and plasma. Such systems and methods provide a pathway to a whole variety of applications including

compact neutron sources (for medical isotope production, nuclear waste remediation, materials research, neutron radiography and tomography), compact photon sources (for chemical production and processing), mass separation and enrichment systems, and reactor cores for fusion for the future generation of energy and for fusion propulsion systems.

[0029] The systems and methods described herein are based on the application of successive, axially symmetric acceleration and adiabatic compression stages to accelerate and heat two compact tori towards each other and ultimately collide and fast magnetically compress the compact tori within a central compression chamber. Figure 1 illustrates the basic layout of a system 10 for forming, accelerating, adiabatically compressing, merging and finally magnetically compressing the compact tori.

[0030] As depicted, the system comprises a staged symmetric sequence of compact tori formation in formation sections 12N and 12S, axial acceleration through sections 12N, 12S, 16N and 16S by fast active magnetic coils 32N, 32S, 36N and 36S, passive adiabatic compression by way of a conically constricting flux conserver in sections 14N, 14S, 18N and 18S, and ultimately merging of the compact tori and final fast magnetic compression in a central compression chamber 20 by fast active magnetic coils 40. As illustrated, the intermediate steps of sufficient axial acceleration followed by adiabatic compression can be repeated multiple times to achieve adequate target conditions before merging and final compression. In this way a reactor can be realized by adding further sections to the depicted system.

[0031] As depicted the formation and accelerations stages or sections 12N, 12S, 16N and 16S and the central compression chamber 20 are preferably cylindrically shaped with walls formed of non-conducting or insulating material such as, e.g., a ceramic. The compressions stages or sections 14N, 14S, 18N and 18S are preferably trunco-conically shaped with walls formed from conducting material such as, e.g., a metal.

[0032] Aside from a magnetic bias field (DC guide field) supplied by slow passive coils 30, the formation sections 12N and 12S, the acceleration sections 16N and 16S, and the compression chamber 20 include modular pulsed power systems that drive fast active magnetic coils 32N, 32S, 36N, 36S and 40. The pulsed power systems enable compact tori to be formed in-situ within the formation sections 12N and 12S and accelerated and injected (=static formation) into the first compression sections 14N and 14S, accelerated in the acceleration sections 16N and 16S and injected into the next compression sections 18N and 18S, and so on, and then be magnetically compressed in the compression chamber 20. The slow passive magnetic coil systems 30 located throughout and along the axis of the system provide an axial magnetic guide field to center the compact tori appropriately.

[0033] Alternatively, the modular pulsed power systems of the formation sections can also drive the fast magnetic coils in a way such that compact tori are formed and accelerated simultaneously (=dynamic formation).

[0034] The systems and methods described herein deploy FRCs, amongst the highest beta plasmas known in magnetic confinement, to provide the starting configuration. Further passive and active compression builds on this highly efficient magnetic topology. The process of using axial acceleration via active fast magnet sections followed by adiabatic compression in simple flux conserving conic sections provides for the most efficient transfer of energy with the least complex pulsed power circuitry. Furthermore, these basic building blocks can be sequenced to take additional advantage of the inherently favorable compressional scaling, i.e. $\Delta p \propto R^4$.

[0035] Based on experimental and theoretical research to date, a precursor experiment as describe by Bystritskii, using FRC starter plasmas has achieved densities of about 10^{17} cm^{-3} at 1 keV. The embodiments proposed herein are estimated to reach densities of about 10^{18} cm^{-3} at 1 keV, while adding further stages and appropriate upgrades to the central chamber and fast magnetic coils can yield ultimate densities of about 10^{18} cm^{-3} at full Lawson conditions.

[0036] In another embodiment, the system is configured to deploy spheromaks instead of FRC starter plasmas.

[0037] In another embodiment, the system comprises a staged asymmetric sequence from a single side of the central compression chamber comprising compact tori formation, axial acceleration by fast active magnetic coils, passive adiabatic compression by way of a conically constricting flux conserver, and ultimately merging of the compact tori and final fast magnetic compression in the central compression chamber. Such an asymmetric system would include a mirror or bounce cone.

[0038] In yet another embodiment, the system comprising a thin cylindrical shell or liner comprised of conductive material such as, e.g., a metal, for fast liner compression within the central compression chamber.

[0039] Fusion concepts today are focused on either steady state or ultra-short pulsed regimes. Both approaches require large capital investment: in steady state magnetic fusion, high expense arises from large superconducting magnets and auxiliary heating/current drive technologies; inertial regimes are dominated by high driver cost due to large energy delivery over nanosecond timescales. The embodiments advanced herein are characterized by compact size and sub-millisecond time scales. This leads to a regime that has relaxed peak power requirements and attractive intermediate time scales.

[0040] Turning in detail to the drawings, as depicted in Figure 1, a system 10 for merging and compressing compact tori plasma includes a central compression chamber 20 and a pair of north and

south diametrically opposed compact tori formation sections 12N and 12S. The first and second formation sections 12N and 12S include a modularized formation and acceleration systems 120 (discuss below in detail with regard to see Figures 2-4) for generating first and second compact plasma tori and axially accelerating and translating the compact tori towards a mid-plane of the compression chamber 20.

[0041] As depicted, the system 10 further includes a first pair of north and south diametrically opposed compression sections 14N and 14S coupled on a first end to an exit end of the north and south formation sections 12N and 12S. The north and south compression sections 14N and 14S being configured to adiabatically compress the compact tori as the compact tori traverse the north and south compression sections 14N and 14S towards the mid-plane of the compression chamber 20.

[0042] As depicted, the system 10 further includes a pair of north and south diametrically opposed acceleration sections 16N and 16S coupled on a first end to a second end of the first pair of north and south compression sections 14N and 14S. The north and south acceleration section 16N and 16S include modularized acceleration systems (discussed below with regard to Figures 2-4) for axially accelerating and translating the compact tori towards the mid-plane of the compression chamber 20.

[0043] As further depicted, the system 10 further includes a second pair of north and south diametrically opposed compression sections 18N and 18S coupled on a first end to a second end of the north and south acceleration sections 16N and 16S and on a second end to first and second diametrically opposed ends of the compression chamber, the second pair of north and south compression sections 18N and 18S being configured to adiabatically compress the compact tori as the compact tori traverse the second pair of north and south compression sections 18N and 18S towards the mid-plane of the compression chamber 20.

[0044] The compression chamber includes a modularized compression systems configured to magnetically compress the compact tori upon collision and merger thereof.

[0045] As depicted the north and south formation sections 12N and 12S, the north and south acceleration sections 16N and 16S and the compression chamber 20 are cylindrically shaped. The diameter of the north and south acceleration sections 16N and 16S is smaller than the diameter of the north and south formation sections 12N and 12S, while the diameter of the compression chamber 20 is than the diameter of the north and south acceleration sections 16N and 16S.

[0046] The first and second pairs of north and south compression sections 14N, 14S, 18N and 18S are truncated conically shaped with their diameter being larger on a first end than on a second end enabling a transition in the overall diameter of the system 10 from the formation sections 12N and 12S to the acceleration sections 16N and 16S to the compression chamber 20. As depicted, the north and south formation sections 12N and 12S, the first pair of north and south compression sections

14N and 14S, the north and south acceleration sections 16N and 16S, and the second pair of north and south compression sections 18N and 18S are axially symmetric.

[0047] As depicted, first and second sets of a plurality of active magnetic coils 32N and 32 are disposed about and axially along the north and south formation sections 12N and 12S, third and fourth sets of a plurality of active magnetic coils 36N and 36S are disposed about and axially along the north and south acceleration sections 16N and 16S, and a fifth set of a plurality of active magnetic coils 40 are disposed about and axially along the compression chamber 20.

[0048] The compression sections 14N, 14S, 18N and 18S are preferably formed from conducting material such as, e.g., a metal, while the central compression chamber 20 and the formation and acceleration sections are 12N, 12S, 16N and 16S are preferably formed from non-conducting or insulating material such as, e.g., a ceramic.

[0049] As depicted, a plurality of DC magnetic coils 30 are disposed about and axially along the central compression chamber 20 and the formation, compression and acceleration sections 12N, 12S, 14N, 14S, 16N, 16S, 18N and 18S to form a bias or DC guide field within and extending axially through the central compression chamber and the formation, compression and acceleration sections.

[0050] Triggering control and switch systems 120, shown in Figures 2-4, are configured to enable a staged symmetric sequence of compact tori formation by active magnetic coils 32N and 32S in the north and south formation sections 12N and 12S, axial acceleration by active magnetic coils 36N and 36S in the north and south acceleration sections 16N and 16S, and compression by active magnetic coils 40 in the compression chamber 20. The triggering control and switch systems 120 are configured to synchronize compact tori formation and acceleration in the north and south formation sections 12N and 12S, compact tori acceleration in the north and south acceleration sections 16N and 16S, and compact tori merge and compression in the compression chamber 20.

[0051] Turning to Figures 2-4, there is individual pulsed power system 120 corresponding to and powering individual ones of the first, second, third, fourth and fifth sets of the plurality of active magnets 32N, 32S, 36N, 36S and 40 of the formation sections 12N and 12S, the acceleration sections 16N and 16S, and the compression chamber 20. In the formation sections, the pulse power system 120 operates on a modified theta-pinch principle to form the compact tori. Figures 2 through 4 illustrate the main building blocks and arrangement of the pulsed power systems 120. The pulsed power system 120 is composed of a modular pulsed power arrangement that consists of individual units (=skids) 122 that each energize a sub-set of coils 132 of a strap assembly 130 (=straps) that wrap around the section tubes 140. Each skid 122 is composed of capacitors 121, inductors 123, fast high current switches 125 and associated trigger 124 and dump circuitry 126. Coordinated operation of these components is achieved via a state-of-the-art trigger and control system 124 and 126 that

allows synchronized timing between the pulsed power systems 120 on each of the formation sections 12N and 12S, the acceleration sections 16N and 16S, and compression chamber 20, and minimizes switching jitter to tens of nanoseconds. The advantage of this modular design is its flexible operation. In the formation sections 12N and 12S, FRCs can be formed in-situ and then accelerated and injected (=static formation) or formed and accelerated at the same time (=dynamic formation). [0052] In operation, a DC guide field is generated by the passive coils 30 within and axially extending through the compression chamber 20, the formation sections 12N and 12S, the acceleration sections 16N and 16S, and the compression sections 14N, 14S, 18N and 18S. Compact tori are then formed and accelerated in a staged symmetric sequence within the formation sections 12N and 12S and the acceleration sections 16N and 16S towards a mid-plane of the central chamber 20, passively adiabatically compressed within the compression sections 14N, 14S, 18N and 18S, and merged and magnetically compressed within the central chamber 20. These steps of forming, accelerating and compressing compact tori results in the compact tori colliding and merging within the central chamber 20.

[0053] The compact tori are formed and accelerated by powering active magnetic coils 32N and 32S extending about and axially along the formation sections 12N and 12S, further accelerated by powering active magnetic coils 35N and 36S extending about and axially along the acceleration sections 16N and 16S, and compressed by powering active magnetic coils 40 extending about and axially along the compression chamber 20. The steps of forming, accelerating and compressing the compact tori further comprises synchronously firing diametrically opposed pairs of active magnetic coils 32N and 32S, and 36N and 36S positioned about and along the formation 12N and 12S and acceleration sections 16N and 16S, and a set of active magnetic coils 40 positioned about and along the compression chamber 20.

[0054] As the compact tori are accelerated towards the mid-plane of the compression chamber 20, the compact tori are compressed as the compact tori translate through the conically constricting flux conservers of the compression stages 14N, 14S, 18N and 18S.

[0055] Turning to Figure 5, an alternative embodiment of a system 100 for merging and compressing compact tori plasma is illustrated. As depicted, the system 100 comprises a staged asymmetric sequence from a single side of the central compression chamber 20. The system 100 includes a single compact toroid formation section 12S, a first compression section 14S coupled on a first end to an exit end of the formation section 12S, an acceleration section 16N coupled on a first end to a second end of the compression section 14S, a second compression section 18S coupled on a first end to a second end of the acceleration section 16S and on a second end to a first end of the compression

chamber 20. A mirror or bounce cone 50 is positioned adjacent the other end of the central compression 20.

[0056] In operation, a first compact toroid is formed and accelerated in a staged sequence within the formation section 12S and then accelerated in one or more acceleration stages 16S towards a mid-plane of the central chamber 20 to collide and merge with a second compact toroid. The first compact toroid is passively adiabatically compressed within one or more compression stages 14S and 18S, and then magnetically compressed as a merged compact toroid with the second compact toroid within the central chamber 20.

[0057] The second compact toroid is formed and accelerated in a staged sequence within the formation section 12S and the one or more acceleration stages 16S towards a mid-plane of the central chamber 20, passively adiabatically compressed within the one or more compression stages, and then biased back toward the mid-plane of the central chamber 20 as it passes through the central chamber 20 with a mirror or bounce cone 50 positioned adjacent an end of the central chamber 20.

[0058] Turning to Figure 6, an alternative embodiment of a system 200 for merging and compressing compact tori plasma is illustrated in a partial detail view showing the compression chamber 20 with diametrically opposed compression section 18N and 18S coupled to opposing sides of the chamber 20. The system 200 further comprise a cylindrical shell or liner 60 positioned within the central compression chamber 20 for fast liner compression.

[0059] While the invention is susceptible to various modifications, and alternative forms, specific examples thereof have been shown in the drawings and are herein described in detail. It should be understood, however, that the invention is not to be limited to the particular forms or methods disclosed, but to the contrary, the invention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the appended claims.

[0060] In the description above, for purposes of explanation only, specific nomenclature is set forth to provide a thorough understanding of the present disclosure. However, it will be apparent to one skilled in the art that these specific details are not required to practice the teachings of the present disclosure.

[0061] The various features of the representative examples and the dependent claims may be combined in ways that are not specifically and explicitly enumerated in order to provide additional useful embodiments of the present teachings. It is also expressly noted that all value ranges or indications of groups of entities disclose every possible intermediate value or intermediate entity for the purpose of original disclosure, as well as for the purpose of restricting the claimed subject matter.

[0062] Systems and methods for merging and compressing compact tori have been disclosed. It is understood that the embodiments described herein are for the purpose of elucidation and should not

be considered limiting the subject matter of the disclosure. Various modifications, uses, substitutions, combinations, improvements, methods of productions without departing from the scope or spirit of the present invention would be evident to a person skilled in the art. For example, the reader is to understand that the specific ordering and combination of process actions described herein is merely illustrative, unless otherwise stated, and the invention can be performed using different or additional process actions, or a different combination or ordering of process actions. As another example, each feature of one embodiment can be mixed and matched with other features shown in other embodiments. Features and processes known to those of ordinary skill may similarly be incorporated as desired. Additionally and obviously, features may be added or subtracted as desired. Accordingly, the invention is not to be restricted except in light of the attached claims and their equivalents.

CLAIMS

What is claimed is:

1. A system for merging and compressing compact tori plasma comprising a compression chamber,
first and second diametrically opposed compact tori formation sections, the first and second formation sections comprising modularized formation and acceleration systems for generating first and second plasma compact tori and axially accelerating the compact tori and translating the compact tori towards a mid-plane of the compression chamber,
first and second diametrically opposed compression sections coupled on a first end to an exit end of the first and second formation sections, the first and second compression sections being configured to adiabatically compress the compact tori as the compact tori traverse the first and second compression sections towards the mid-plane of the compression chamber,
first and second diametrically opposed acceleration sections coupled on a first end to a second end of the first and second compression sections, the first and second acceleration section comprising modularized acceleration systems for axially accelerating the compact tori and translating the compact tori towards the mid-plane of the compression chamber, and
third and fourth diametrically opposed compression sections coupled on a first end to a second end of the first and second acceleration sections and on a second end to first and second diametrically opposed ends of the compression chamber, the third and fourth compression sections being configured to adiabatically compress the compact tori as the compact tori traverse the third and fourth compression sections towards the mid-plane of the compression chamber.
2. The system of claim 1, wherein the compression chamber is configured to magnetically compressing the compact tori upon collision and merger thereof.
3. The system of claim 1, wherein the compression chamber comprises a modularized acceleration system for magnetically compressing the compact tori upon collision and merger thereof.
4. The system of claims 1 through 3, wherein the first and second formation sections, the first and second acceleration sections and the compression chamber are cylindrically shaped, the diameter of the first and second acceleration sections being smaller than the diameter of the first and

second formation sections and the diameter of the compression chamber being than the diameter of the first and second acceleration sections.

5. The system of claims 1 through 4, wherein the first, second, third and fourth compression sections are truncated conically shaped with the diameter of the first, second, third and fourth compression section being larger on first end than on the second end.

6. The system of claims 1 through 5, wherein the first and second formation sections, the first and second compression sections, the first and second acceleration sections and the third and fourth compression sections are axially symmetric.

7. The system of claims 1 through 6, wherein a plurality of active magnetic coils are disposed about and axially along the first and second formation sections, the first and second acceleration sections, and the compression chamber.

8. The system of claims 1 through 7, further comprising triggering control and switch systems configured to enable a staged symmetric sequence of compact tori formation in the first and second formation sections and axial acceleration by active magnetic coils in the first and second acceleration sections.

9. The system of claims 1 through 8, wherein the triggering control and switch systems are configured to synchronize the compact tori formation and acceleration in the first and second formation sections and synchronize the compact tori acceleration in the first and second acceleration sections.

10. The system of claim 9, wherein the triggering control and switch systems are further configured to synchronize the magnetic compression with the compact tori formation and acceleration in the first and second formation sections and the compact tori acceleration in the first and second acceleration sections.

11. The systems of claims 1 through 10 further comprising a plurality of DC magnetic coils disposed about and axially along the central compression chamber and the formation, compression and acceleration sections to form a bias or DC guide field within and extending axially through the central compression chamber and the formation, compression and acceleration sections.

12. The system of claims 1 through 11 further comprising a cylindrical shell or liner positioned within the central compression chamber for fast liner compression.

13. A system for merging and compressing compact tori plasma comprising
a compression chamber,
a compact toroid formation section, the formation section comprising modularized formation and acceleration sections for generating a compact toroid and axially accelerating the compact toroid and translating the compact toroid towards a mid-plane of the compression chamber,
a first compression section coupled on a first end to an exit end of the formation section, the first compression section being configured to adiabatically compress the compact toroid as the compact toroid traverses the first compression section towards the mid-plane of the compression chamber,
an acceleration section coupled on a first end to a second end of the first compression section, the acceleration section comprising modularized acceleration systems for axially accelerating the compact toroid and translating the compact toroid towards the mid-plane of the compression chamber,
a second compression sections coupled on a first end to a second end of the acceleration section and on a second end to a first end of the compression chamber, the second compression section being configured to adiabatically compress the compact toroid as the compact toroid traverses the second compression section towards the mid-plane of the compression chamber.

14. The system of claim 13, wherein the compression chamber is configured to magnetically compress the compact toroid.

15. The system of claims 13 and 14, wherein the formation section, the acceleration section and the compression chamber are cylindrically shaped, the diameter of the acceleration section being smaller than the diameter of the formation section and the diameter of the compression chamber being smaller than the diameter of the acceleration section.

16. The system of claims 13 through 15, wherein the first and second compression sections are trunco-conically shaped with the diameter of the first and second compression sections being larger on the first end than on the second end.

17. The system of claims 13 through 16, wherein the formation section, the first and second compression sections, the acceleration section, and the compression chamber are axially aligned.

18. The system of claims 13 through 17, wherein a plurality of active magnetic coils are disposed about and axially along the formation section, the acceleration section, and the compression chamber.

19. The system of claims 13 through 18, further comprising triggering control and switch systems configured to enable a staged sequence of compact toroid formation and axial acceleration by active magnetic coils.

20. The system of claim 19, wherein the triggering control and switch systems are further configured to enable magnetic compression of the compact toroid by active magnetic coils in a staged sequence following the staged sequence of compact toroid formation and axial acceleration by active magnetic coils.

21. The system of claim 19, wherein the triggering control and switch systems are configured to synchronize the compact toroid formation and acceleration in the formation section and synchronize the compact toroid acceleration in the acceleration section with the positioning of a second compact toroid at the mid-plane of the compression chamber.

22. The system of claim 20, wherein the triggering control and switch systems are further configured to synchronize the compression of the compact toroid and the second compact toroid with the compact toroid formation and acceleration in the formation section, the compact toroid acceleration in the acceleration section and the positioning of the second compact toroid at the mid-plane of the compression chamber.

23. The systems of claims 13 through 22 further comprising a plurality of DC magnetic coils disposed about and axially along the central compression chamber and the formation, compression and acceleration sections to form a bias or DC guide field within and extending axially through the central compression chamber and the formation, compression and acceleration sections.

24. The system of claims 13 through 23 further comprising a cylindrical shell or liner positioned within the central compression chamber for fast liner compression.

25. The system of claims 13 through 24 further comprising one of a mirror and a bounce cone coupled to a second end of the central compression chamber.

26. A system for merging and compressing compact tori plasma comprising
a central chamber,
a pair of diametrically opposed formation sections,
one or more diametrically opposed pairs of acceleration sections, and
one or more diametrically opposed pairs of compression sections interposing the formation sections and acceleration sections adjacent to the formation sections and interposing the central chamber and acceleration sections adjacent to the central chamber,
wherein the system is configured to enable a staged symmetric sequence of compact tori formation, axial acceleration by active magnetic coils about the formation and acceleration sections, passive adiabatic compression of the compact tori within a conically constricting flux conserver of the compression sections, and magnetic compression within the central chamber.

27. The system of claim 26, wherein the compression chamber is configured to magnetically compress the compact tori upon collision and merger thereof.

28. The system of claims 26 and 27, wherein the formation sections, the acceleration sections and the central chamber are cylindrically shaped, the diameter of the acceleration sections being smaller than the diameter of the formation sections and smaller than the preceding acceleration section in a direction from the formation section to the central chamber, and the diameter of the central chamber being smaller than the diameter of the acceleration sections.

29. The system of claims 26 through 28, wherein the compression sections are trunco-conically shaped with the diameter of the compression section being larger on a first end than on a second end, wherein the second end of each compression section being closer to the central chamber than the first end.

30. The system of claims 26 through 29, wherein the formation sections, the one or more pairs of compression sections, and the one or more pairs of acceleration sections are axially symmetric.

31. The system of claims 26 through 30, wherein a plurality of active magnetic coils are disposed about and axially along the formation sections, the acceleration sections, and the central chamber.

32. The system of claims 26 through 31, further comprising triggering control and switch systems configured to enable staged symmetric sequence of compact tori formation in the formation sections and axial acceleration in the acceleration sections.

33. The system of claim 32, wherein the triggering control and switch systems are further configured to enable magnetic compression of the compact tori by active magnetic coils in a staged sequence following the staged sequence of compact tori formation and axial acceleration by active magnetic coils.

34. The system of claim 32, wherein the triggering control and switch systems are configured to synchronize the compact tori formation and acceleration in the pair of formation sections and synchronize the compact tori acceleration in the one or more pairs of acceleration sections.

35. The system of claim 33, wherein the triggering control and switch systems are further configured to synchronize the compression of the compact tori with the compact tori formation and acceleration in the formation section and the compact tori acceleration in the acceleration section.

36. The system of claims 26 through 35 wherein the compression sections interpose the central chamber and adjacent acceleration sections.

37. The systems of claims 26 through 36 further comprising a plurality of DC magnetic coils disposed about and axially along the central compression chamber and the formation, compression and acceleration sections to form a bias or DC guide field within and extending axially through the central compression chamber and the formation, compression and acceleration sections.

38. The system of claims 26 through 437 further comprising a cylindrical shell or liner positioned within the central compression chamber for fast liner compression.

39. A method of merging and compressing compact tori plasma within in a system comprising a central chamber, diametrically opposed formation sections, one or more acceleration stages, and a plurality compression stages interposing the formation sections and adjacent acceleration stages, and the central chamber and adjacent acceleration stages, the steps comprising forming and accelerating compact tori in a staged symmetric sequence within the formation sections and the acceleration stages towards a mid-plane of the central chamber, passively adiabatically compressing the compact tori within the compression sections, and magnetically compressing a merged compact tori within the central chamber.

40. The method of claim 39 wherein the steps of forming, accelerating and compressing compact tori results in the compact tori colliding and merging within the central chamber.

41. The method of claims 39 and 40 wherein the steps of forming and accelerating the compact tori includes powering active magnetic coils about and axially along the formation sections and acceleration stages.

42. The method of claims 39 through 41, wherein the step of compressing the compact tori includes translating the compact tori through conically constricting flux conservers of the compression stages.

43. The method of claims 39 through 42, wherein the step of forming and accelerating the compact tori further comprises synchronously firing diametrically opposed pairs of active magnetic coils positioned about and along the formation and acceleration sections.

44. The method of claim 43, wherein the step of magnetically compressing a merged compact tori comprises synchronously firing active magnetic coils positioned about and along the compression chamber with the firing active magnetic coils positioned about and along the formation and acceleration sections.

45. The method of claims 39 through 44 wherein the compression sections interpose the central chamber and adjacent acceleration stages.

46. The method of claims 39 through 45 further comprising the step of generating a DC guide field within and axially extending through the compression chamber, the formation sections, the acceleration stages, and the compression stages.

47. A method of merging and compressing compact tori plasma within in a system comprising a central chamber, a formation section, one or more acceleration stages, and one or more compression stages interposing the formation section and an adjacent acceleration stage and adjacent acceleration stages, the steps comprising

forming and accelerating a first compact toroid in a staged sequence within the formation section and the one or more acceleration stages towards a mid-plane of the central chamber to collide and merge with a second compact toroid,

passively adiabatically compressing the first compact toroid within the one or more compression stages, and

magnetically compressing a merged compact toroid of the first and second compact tori within the central chamber.

48. The method of claim 47 wherein the steps of forming, accelerating and compressing the first compact toroid results in the first compact toroid colliding and merging with the second compact toroid within the central chamber.

49. The method of claims 47 and 48 wherein the steps of forming and accelerating the first compact toroid include powering active magnetic coils about and axially along the formation section and the one or more acceleration stages.

50. The method of claims 47 through 55, wherein the step of compressing the first compact toroid includes translating the compact toroid through a conically constricting flux conserver of the one or more compression stages.

51. The method of claims 47 through 56, wherein the step of forming and accelerating the first compact toroid further comprises synchronously firing the active magnetic coils positioned about and along the formation and acceleration sections with the positioning of the second compact toroid within the central chamber.

52. The method of claims 47 through 51 wherein the one or more compression stages interpose the central chamber and an adjacent acceleration stage.

53. The method of claims 47 through 52 further comprising the step of generating a DC guide field within and axially extending through the compression chamber, the formation sections, the acceleration stages, and the compression stages.

54. The method of claims 47 through 53 further comprising the steps
forming and accelerating the second compact toroid in a staged sequence within the formation section and the one or more acceleration stages towards a mid-plane of the central chamber,
passively adiabatically compressing the second compact toroid within the one or more compression stages, and
biasing the second compact toroid back toward the mid-plane of the central chamber as it passes through the central chamber with a mirror positioned adjacent an end of the central chamber.

55. The method of claims 47 through 54 further comprising the steps
forming and accelerating the second compact toroid in a staged sequence within the formation section and the one or more acceleration stages towards a mid-plane of the central chamber,
passively adiabatically compressing the second compact toroid within the one or more compression stages, and
biasing the second compact toroid back toward the mid-plane of the central chamber as it passes through the central chamber with a bounce cone positioned adjacent an end of the central chamber.

56. The system of claims 1 through 38 wherein the compact tori are one of FRC and spheromak starter plasmas.

57. The system of claims 1 through 38 wherein the compression sections are formed from conducting material and the central compression chamber and the formation and acceleration sections are formed from non-conducting material.

58. The method of claims 39 through 55 wherein the compact tori are one of FRC and spheromak starter plasmas.

59. The method of claims 39 through 55 wherein the compression sections are formed from conducting material and the central compression chamber and the formation and acceleration sections are formed from non-conducting material.