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IAEA TECDOC SERIES

IAEA-TECDOC-1875

Conceptual Development of Steady State Compact Fusion Neutron Sources

Report of a Coordinated Research Project

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CONCEPTUAL DEVELOPMENT OF STEADY STATE COMPACT FUSION NEUTRON SOURCES

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CONCEPTUAL DEVELOPMENT OF STEADY STATE COMPACT FUSION NEUTRON SOURCES

REPORT OF A COORDINATED RESEARCH PROJECT

INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

Fusion neutron sources have many important practical uses, including for triggering fission reactions, manufacturing medical isotopes, testing materials and components for use in future fusion reactors, and facilitating the production of various isotopes such as tritium. All these applications can be potentially improved by achieving high energy compact fusion neutron sources (CFNSs).

In 2012–2016, the IAEA carried out a coordinated research project entitled Conceptual Development of Steady-State Compact Fusion Neutron Sources. A total of 11 institutions from 8 Member States (China, Latvia, Poland, Russian Federation, Sweden, Ukraine, United Kingdom and United States of America). worked together to investigate a wide range of power options for CFNSs with the aim of developing a conceptual framework for a variety of steady state CFNSs. Work envisioned under the project was related to the development of concepts and conceptual designs for both low and high power CFNSs. Through the collaboration of experts in the participating Member States, the project laid the foundation for practical applications of intense fusion neutron sources.

The present publication is a compilation of the project's main results and findings; the supplementary files available on-line present the eight country reports with additional relevant technical details. The IAEA officers responsible for this publication were M. Barbarino and S.M. Gonzalez de Vicente of the Division of Physical and Chemical Sciences.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

At present, fusion research is mostly aimed at energy production. However, it is well known that in a tokamak the optimal conditions for energy production are different from those for maximum neutron production. Emphasis on fusion research for neutron production will, therefore, broaden the scope of fusion research, in particular in exploring plasma modes that are more suited for neutron production. The motivation is provided by the large number of possible applications of copious fusion neutrons. High energy fusion neutrons are valuable for a range of technological applications such as manufacturing medical isotopes and testing materials and components for use in future fusion reactors. The development of fusion nuclear technologies requires steady-state devices with high output of high energy neutrons, complementary to International Fusion Materials Irradiation Facility (IFMIF) and existing low-power neutron sources. In particular, the engineering design of a demonstration fusion power plant (DEMO) will require component test facilities with 14 MeV neutrons to test and qualify different components and modules.

In addition, a wide variety of other applications exist including (i) the detection of specific elements or isotopes in complex environments; (ii) radiotherapy; (iii) the alteration of electrical, optical or mechanical properties of materials and other material studies; (iv) the production of hydrogen (via high-temperature electrolysis); (v) the production of tritium (scarce due to its short half-life); and (vi) many other non-electric applications of fusion. These possible commercial non-electrical applications were recently analysed in detail in the FESAC and ARIES (USA) studies. But the most obvious non-electric application of a fusion neutron source is to aid the presently expanding nuclear energy industry. The application of fast fusion neutrons can convert the huge stockpiles of depleted uranium into fresh fuel and can help reduce waste problems by transmutation.

All these applications can be potentially improved by achieving high-energy Compact Fusion Neutron Sources (CFNS), and pre-conceptual studies on the development of steady-state CFNS are now on-going in several Member States. The majority of these investigations are based on the Spherical Tokamak (ST) concept, but some activities explore the mirror machines. CFNS devices based on the ST concept devices were proposed in the USA, China, UK, Brazil, Kazakhstan and the Russian Federation. Mirror machines-based CFNS are being studied in Ukraine, USA, Sweden, Russian Federation and Germany.

1.2. OBJECTIVE

In 2012–2016, the IAEA organized and implemented the Coordinated Research Project (CRP) on “Conceptual Development of Steady-State Compact Fusion Neutron Sources”. A total of 11 institutions from 8 Member States (China, Latvia, Poland, Russian Federation, Sweden, Unites Kingdom, United States of America, and Ukraine) cooperated with the main objective to investigate a wide range of power options for CFNS.

This publication is a compilation of the main results and findings of the CRP and the supplementary files accompanying this publication contains 8 reports with additional relevant technical details. The overall objectives of this TECDOC are to:

- Describe options for steady-state CFNS with typical fusion power in the range 1–100 MW (intensity 3.5×10^{17}–10^{19} n/s), neutron wall loading in the range 0.1–1 MW/m^2 based on magnetic confinement approaches such as tokamaks, stellarators and mirror machines;
- Give plasma parameter spaces for optimizing core and edge plasma performance for neutron production at fusion energy gain value Q = 0.1–1;
- Formulate concepts for enabling technologies and associated materials: this will include the magnet systems, vacuum vessel, divertor, blankets, the heating and current drive systems, the pumping, cooling and fuelling systems, the tritium plant, diagnostics, the remote handling system;
- Provide safety considerations;
- Improve simulation data for plasma, nuclear processes and their interaction.

1.3. SCOPE

The scope of this publication is to investigate options for low and high power CFNS under operational domains with optimized core and edge plasma performance.

1.4. STRUCTURE

This TECDOC is divided into two standalone but interrelated parts:

- This publication, which describes the activities and provides main results and findings of the CRP, and it is organized as follows:
    i. Section 2 describes the activities of the CRP, including joint and individual R&D activities.
    ii. Section 3 highlights the results from joint and individual activities.
    iii. Section 4 summarises the findings and recommends to the supplementary files for further reading.
- The supplementary files accompanying this publication which contains 8 reports with additional relevant technical details.

2. CRP ACTIVITIES

11 institutions from 8 Member States participated in this CRP:

- Institute of Nuclear Energy Safety Technology CAS–FDS Team, Hefei, China;
- Institute of Physics University of Latvia (IPUL), Riga, Latvia;
- Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw, Poland;
- A.A. Baikov Institute of Metallurgy and Material Sciences, Moscow, Russian Federation;
- NRC ‘Kurchatov Institute’ Moscow, Russian Federation;
- Angstroem Laboratory; University of Uppsala, Sweden;
- Tokamak Solutions UK Ltd, Culham Science Centre, United Kingdom;
- Institute of Plasma Physics of the National Centre ‘Kharkiv Institute of Physics and Technology’, Kharkiv, Ukraine;
- Princeton Plasma Physics Laboratory (PPPL), USA;
- University of Texas at Austin, USA;
- Woodruff Scientific., Seattle, USA.

Designs based on spherical and conventional tokamaks, stellarator–mirror devices, gas dynamic trap, spheromak and dense plasma focuses were proposed and developed. The design solutions were found and assessed, which confirmed feasibility of realization of pilot facilities with DT-fusion power 1–100 MW.

Integrated design of CFNS corresponded to conceptual level but several enabling systems were developed more thoroughly. The presented designs and results on manufacturing mock-ups and complete systems for electromagnetic systems, in-vessel components, heating and current drive systems, diagnostics and power supplies indicated the starting transition of the CFNS activity to the engineering design stage.

There was also interest in collaborative activity in development of fusion–fission hybrid systems as a potential solution for tritium breeding for fusion devices, fissile nuclides breeding for nuclear reactors and minor actinides and incineration of the long-life radionuclides as radiotoxic products of the nuclear fuel cycle.

Last, the CRP clarified major areas of early applications of CFNS and enabling technologies which may complement the fusion development especially in the fields of steady state operations, material studies and fusion nuclear science. Detailed overviews of corresponding joint and individual activities are presented in the next sub-section.

2.1. JOINT ACTIVITIES

The CRP stimulated a number of joint activities between participants. The main area of collaboration was aimed at: assessment of conceptual and engineering design parameters for compact fusion neutron sources in the range of fusion power from 1 MW to 100 MW, for the fusion energy multiplication factor $0.1 < Q < 1$, and for neutron rates of the order of 10^{17}–10^{19} n/s; development of magnet technology including application of Low Temperature Superconductors (LTS), High Temperature Superconductors (HTS) and copper alloys; development of new divertor concepts including application of liquid Li; transport and scenario simulations; development of non-tokamak CFNS (Figs 1–2).

The NRC Kurchatov Institute (RF) initiated joint programmes in plasma simulation and technology development with several parties. They included plasma simulations, manufacturing and operation tests of a twisted central post of the toroidal field Cu magnet system with Tokamak Energy (UK); joint activity with IPUL (Latvia) on evaluation of requirements for a high power divertor of a steady-state FNS; divertor and lithium technology studies in collaboration with the University of Texas at Austin (USA), the PPPL (USA); Collaborative research on Fusion Neutron Sources (FNS) based on open systems and on development of NBI for FNS with the Budker Institute, Novosibirsk, (RF).

Recent advances in HTS magnet technology potentially capable of accessing current densities of up to 600 MA/m^2 (and possibly higher) combined with operation at higher temperature than LTS for associated reductions in refrigeration power in the presence of increased nuclear heating may make it possible for lower aspect ratio superconducting configurations to be advantageous for FNS applications. These considerations motivated joint studies performed at PPPL (USA), Woodruff Scientific (USA) and Tokamak Energy (UK) of FNS performance versus aspect ratio when high-field and high-current-density rare earth barium copper oxide (REBCO) superconducting HTS toroidal field magnets were utilized.

The development of a liquid Li divertor for compact FNS was pursued within the collaboration between Tokamak Energy, (UK), NRC Kurchatov Institute, (RF), and IPUL, (Latvia). Studies of hydrogen isotopes retention in Li under irradiation in a nuclear reactor were conducted in the collaboration among IPUL, (Latvia) and Tokamak Energy, (UK).

The University of Texas (USA) developed collaboration and joint programme on development of the advanced divertors with PPPL (USA). Woodruff Scientific (USA) has supported a joint programme of R&D with Tokamak Energy, (UK), on simulations of MHD stability and scenarios for a prototype compact FNS (ST40), as well as for systems analysis.

Collaboration between Uppsala University (Sweden) and KhIPT at Kharkov (Ukraine) on magnetic coil design, plasma confinement and heating, and the development of a CFNS based on the mirror and stellarator–mirror concepts resulted in proposals of different new concepts for CFNS. The optimization of the Gas Dynamic Trap (GDT) concept — illustred in Fig.1 — with respect to the electron temperature using electron cyclotron resonance heating has been pursued between the Budker Institute (Russian Federation) and INEST (China). R&D activities on improving the technological characteristics of dense plasma focus devices (Fig. 2) were jointly pursued by the A. A. Baikov Institute (Russian Federation) and IPPLM (Poland).

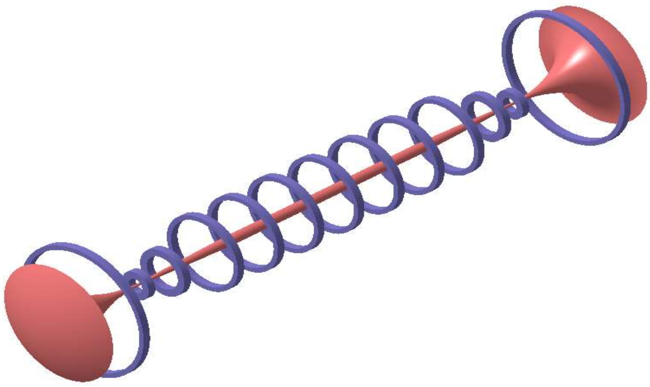

FIG.1. An illustration of the Gas Dynamic Trap configuration: Axisymmetric magnetic coils establish simple mirror configuration and the magnetic field has favorable curvature.

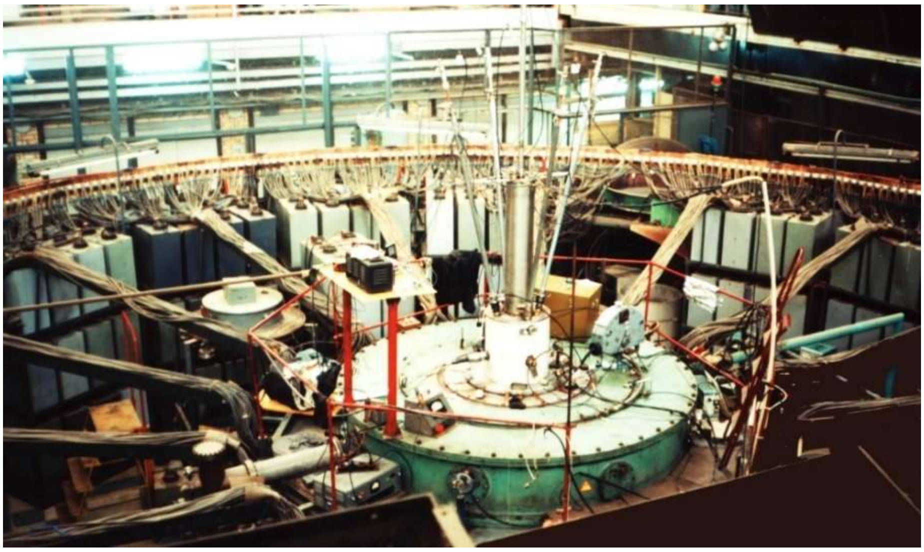

FIG. 2. Plasma Focus at Kurchatov Institute, Russian Federation.

These activities promoted active exchange of information (e.g. joint publications and meeting presentations) and transfer of knowledge (e.g. design assistance) among the CRP participants.

2.2. INDIVIDUAL ACTIVITIES

Activities performed at the participating institutions fall into the following topic categories:

— Conceptual designs for high and low power fusion neutron sources;
— Formulation of concepts for enabling technologies;
— Simulations;
— Safety considerations.

2.2.1. Conceptual designs for high and low power fusion neutron sources

NRC Kurchatov Institute (Russian Federation), Tokamak Energy (United Kingdom), University of Texas–Austin (USA) and PPPL (USA) performed design studies of tokamak based Compact Fusion Neutron Sources (CFNS).

Institute of Nuclear Energy Safety Technology (China), Uppsala University (Sweden) and Institute of Plasma Physics NSC KhIPT (Ukraine) performed conceptual design studies of FNS based on open and stellarator–mirror systems.

IPPLM (Poland) and A. A. Baikov Institute, (Russian Federation) developed FNS based on dense plasma focus.

Research performed by Woodruff Scientific (USA), was dedicated to conceptual studies of the spheromak-based FNS.

2.2.2. Formulation of concepts for enabling technologies

Validated technologies and development of concepts for enabling technologies fall into several groups of activities (i.e. development of advanced magnets, vacuum vessel, first wall materials, divertor, power systems, diagnostics, fuel cycle, remote handling and maintenance).

Magnet technologies for CFNS based on Cu and Al alloys, LTS and HTS were developed by NRC Kurchatov Institute (Russian Federation), University of Texas–Austin (USA), PPPL (USA), Woodruff Scientific (USA), Institute of Nuclear Energy Safety Technology (China), Uppsala University (Sweden) and Tokamak Energy (United Kingdom).

Vacuum vessel, first wall materials and in-vessel components, blanket, divertor design and structural materials studies were performed by NRC Kurchatov Institute (Russian Federation), University of Texas (USA), PPPL (USA), Institute of Nuclear Energy Safety Technology CAS (China), IPUL (Latvia) and Tokamak Energy (United Kingdom).

New concepts for power supply systems were investigated by Tokamak Energy (UK) and Woodruff Scientific (USA).

Heating and current drive systems were developed by Budker Institute (Russian Federation), NRC Kurchatov Institute (Russian Federation), PPPL (USA) and Tokamak Energy (United Kingdom).

Diagnostics development and selection of diagnostics needed for operations in the nuclear environment were performed by NRC Kurchatov Institute (Russian Federation), PPPL (USA), Woodruff Scientific (USA) and Tokamak Energy (United Kingdom).

Tritium and hybrid fuel cycle concepts were developed by NRC Kurchatov Institute (Russian Federation), PPPL (USA), Budker Institute (Russian Federation), University of Texas–Austin (USA) and Institute of Nuclear Energy Safety Technology (China).

Remote handling and other issues connected with maintenance and decommissioning of nuclear facilities were addressed in studies performed by NRC Kurchatov Institute (Russian Federation), PPPL (USA), University of Texas–Austin (USA) and Institute of Nuclear Energy Safety Technology (China).

2.2.3. Simulations

All participants contributed to development of simulation tools and performed studies using computer simulations to develop and justify technical solutions in many areas of the CFNS design. A broad range of simulation capabilities were developed during the course of this CRP. Those include development and application of computational tools for transport, scenario, equilibrium and stability simulations of CFNS plasmas, materials, nuclear processes and their interaction, economic analysis etc.

A number of System Codes has been developed and used in different studies. More sophisticated codes were widely used by many CRP participants for plasma and fast particles transport and scenario analysis, MHD and vertical stability analysis, i.e. ASTRA, NUBEAM, TRANSP, DINA, CORSICA, UEDGE, VMEC, RZIP. Simulations of the SOL and divertor were carried out using the SOLPS and EIRENE codes by PPPL (USA) and Tokamak Energy (UK).

A code for evaluation of the current drive and the neutron spectra for beam–plasma interaction (nYield) was developed and benchmarked with NUBEAM at NRC Kurchatov Institute (Russian Federation). Also, a Monte-Carlo based model was developed for neutronics simulations of neutron flows, nuclear reactions for breeding, transmutation and energy production, and applied to support the FNS–ST and DEMO–FNS designs. Detailed simulations with the nonlinear gyrokinetic codes GENE and GS2 were performed in studies of the anomalous transport in CFNS by Tokamak Energy (UK), PPPL (USA) and Woodruff Scientific (USA).

Uppsala University (Sweden) and Institute of Plasma Physics NSC KhIPT (Ukraine) developed a 2D kinetic code for trapped ions in mirror and stellarator–mirror concepts, a 2D radio-frequency field simulation code and a 0D isotope balance evolution code. Simultaneous integrated computations for the plasma, coil design and neutrons were fit to each other as a combined tool for the development of a FNS.

Device and component computer models were developed for examining mechanical stresses and thermal loads, for use in commercial codes such as COMSOL and ANSYS by many participants.

For material studies, the 3D CAD models have been coupled with the General Monte Carlo N-Particle (MCNP) Transport Code using the DAGMC code. The FISPAC code was also used by Tokamak Energy (UK) for detailed material studies. For the spheromak compression concept, MCNP6 code was used for engineering designs of diagnostic and passive stabilizer components by Woodruff Scientific (USA). The shielding performance of GDT2–FNS was analysed using the Super Monte Carlo Calculation Program for Nuclear and Radiation Process (SuperMC) code by Uppsala University (Sweden).

The FDS team of the Institute of Nuclear Energy Safety Technology (China) updated the System Analysis Program for Parameters Optimization and Economic Assessment of Fusion Reactor (SYSCODE) for calculation of GDT plasma parameters. The integrated multi-functional CAD-based SuperMC was used for the numerical simulation and the performance analysis of fission blanket of FDS–GDT3.

IPPLM (Poland) developed numerical codes (2D code based on non-ideal MHD model and 2D Snow–Plough code) for optimum architecture of the neutron generator selection.

The A. A. Baikov Institute developed specific geometries and input files for MCNP computations for the DPF device, its environment and surrounding structure (designed to mimic the chamber of a large fusion device based on the dense plasma focus).

2.2.4. Safety considerations

Safety and regulation assessments of devices, sites, operations and other activities were important aspects of all design studies of CFNS. Detailed studies addressed impact of safety issues on the choice of materials, designs of specific subsystems, power supplies, methodology of site choice and full complement with general health and safety requirements for tokamak and GDT based CFNS by NRC Kurchatov Institute (Russian Federation), Tokamak Energy (UK), PPPL (USA), Institute of Nuclear Energy Safety Technology (China).

For the mirror and stellarator–mirror concepts, the degree of subcriticality needed for reactor safety was analyzed by Uppsala University (Sweden), with respect to LOCA, LOFA, void of coolant and replacement of lead–bismuth coolant by water. Designs for shielding against neutron irradiation to surrounding space were based on results from numerical MNCPX calculations. A vertical orientation was considered for the SFLM to provide passive coolant circulation for removal of decay heat.

For GDT2–FNS, the shielding against the high flux of fast neutrons and the tritium inventory were identified as the key issues of nuclear safety in studies of the Institute of Nuclear Energy Safety Technology (China). The shielding performance was carefully calculated using the SuperMC code. The public early dose was evaluated for the accidental release into the atmosphere of one gram of tritium, activated tungsten dust, activated corrosion products and activated gas (argon), respectively.

Dense plasma focus devices of few kJ capacitor bank energy are characterized by the absence of fissile materials and lifetime neutron yield less than 10^{15} n/s. Considerations for safe operation of the device were formulated by the IPPLM (Poland), for time-averaged neutron intensity exceeding 10^{12} n/s. For dense plasma focus based neutron sources of tens MJ level, an analysis of radiation hazards for the operating staff (connected with activation of the neutron generator elements) was performed.

3. IMPACT OF THE CRP

The activities carried out in the framework of this CRP have produced a substantial number of publications. The results from both the joint activities and from the activities at the participanting insitutions are summarized in the following Sections.

3.1. RESULTS FROM JOINT ACTIVITIES

In collaboration with Tokamak Energy (UK), the NRC Kurchatov Institute (RF) completed a conceptual design of a steady-state CFNS with Cu magnets. Presentations based on joint projects were given at several conferences: FEC, FNS, FUNFI, Zvenigorod, VNS.

Coordinated research activities in collaboration of Tokamak Energy (UK) and PPPL (USA) and Woodruff Scientific (USA), on development of High Temperature Superconducting magnets for steady state CFNS resulted in joint design studies and publications, followed by implementation of HTS technology on GOLEM (Czech Republic) and ST25–HTS tokamaks. Design of the ST40 tokamak was completed based on results of collaborative activities with the NRC Kurchatov Institute (RF) on design studies of a compact FNS based on a spherical tokamak with Cu magnets. Development of a liquid Li divertor for compact FNS was performed by IPUL (Latvia) in collaboration with Tokamak Energy (UK) and the NRC Kurchatov Institute (RF), resulting in the construction of a prototype divertor loop. Studies of hydrogen isotope retention in Li under irradiation from a nuclear reactor were performed by IPUL (Latvia) in collaboration with Tokamak Energy (UK), resulting in a database of tritium retention under irradiation.

Joint activities between Woodruff Scientific (USA) and Tokamak Energy (UK) were performed in the development of a design point for ST40 spherical tokamak.

University of Texas at Austin (USA) collaborated with PPPL (USA) on the design of an advanced divertor for the Fusion Nuclear Science Facility (FNSF).

Collaboration between Khipt at Kharkiv (Ukraine) and Uppsala University (SW) resulted in the conceptual design of a small Straight Field Line Mirror (SFLM) hybrid device. An international consortium for this project was created.

3.2. RESULTS FROM INDIVIDUAL ACTIVITIES

A wide range of power options were investigated for CFNS, spanning 1–100 MW range, and some at even lower power opening up a wider range of possible applications of fusion neutron sources (see Section 3.2.1). For all concepts investigated, optimization of the plasma conditions for neutron production was performed (see Section 3.2.2). Validated technologies fall into several groupings (e.g. magnets, vacuum vessel, first wall materials, power systems and diagnostics). Progress was made in validated technologies by those groups with experimental programmes (see Section 3.2.3). Validated codes were used to simulate the dynamics of plasma-material interaction as well as the response of the materials to heat and particle loads for most concepts (see Section 3.2.4). For all CFNS designs, safety analysis of plasma accidents was performed (see Section 3.2.5).

3.2.1. Compact fusion neutron source conceptual designs

CFNS options span the 1–100MW range, and some at even lower power opening up a wider range of possible applications of fusion neutron sources. The results can be summarized as follows:

- High power tokamak options (above 100 MW) were developed by the University of Texas–Austin (USA) with a primary focus on the Fusion–fission hybrid to assist the rejuvenation of nuclear energy by making fission energy greener (minimizing radio–toxic wastes) and sustainable (breeding fissile fuel U–233 from abundant fertile material Th–

232). Their rather compact, lightweight, flexible, and removable fusion module (CFNS) is enabled by advanced divertor configurations like the Super-X such new magnetic configurations are needed to handle the (enormous) heat exhaust problem characteristic to high power compact machines. The expected features of advanced divertors (predicted through simulations and theoretical predictions) are, currently, being investigated experimentally on DIIID (USA); and, soon new divertor configurations (Super-X) will be tested on MAST–U (UK).

- Conceptual design studies were developed for both high and low power options by the NRC Kurchatov Institute including the FNS–ST (major radius R = 0.5 m, additional heating power P_b = 10 MW, neutron yield 10^{18} n/s) and DEMO–FNS (major radius R = 2.5–3.2 m, P_b = 30 MW, neutron yield 10^{19} n/s). Engineering design points were developed for a spherical tokamak ST40 that is currently under construction at Tokamak Energy (UK). Scenarios for heating and current drive were developed for this device.
- The FNSF concept (Fig. 3) was under development by a wide collaboration of Institutions including CRP members: PPPL (USA), University of Texas–Austin (USA) and Tokamak Energy (UK).
- The conceptual and engineering design for a 1 MW (peak power) fusion neutron source (scalable up to 20 MW) based on the adiabatic compression of a spheromak was completed by Woodruff Scientific (USA).
- Design studies of Compact fusion–fission Tokamak based on the spherical tokamak were developed by the Institute of Physics at the University of Latvia for transmutation of industrial radioactive waste with specific goal to deal with radioactive waste deposited in the Baldone site ‘Radone’ Repository in Latvia.
- Concept and conceptual design of steady-state neutron sources and hybrid reactors were investigated by University of Uppsala (Sweden) and Kharkiv Institute (Ukraine) for both low and high power for stellarator–mirror concept/device (kinetic calculations and the stellarator scaling were used).
- A series of conceptual designs of GDT (Fig. 4) based on fusion neutron source were developed by the FDS, China within the scientific research objectives, with the following plasma parameters: FDS–GDT1 (L = 13 m, B = 23/0.7 T, P_f = 0.45 MW), FDS–GDT2 (L = 17 m, B = 26/1.4 T, P_f = 3 MW), FDS–GDT3 (L = 25 m, B = 40/2.3 T, P_f = 15 MW).
- Concept of low power CFNS based on Plasma-Focus was proposed by IPPLM (Poland) after extensive analysis of various configuration models with energetics on 10 MJ level. The A. A. Baikov Institute (Russian Federation) tested a method for a characterization of a CFNS facility as an absorber–scatterer of fusion neutrons by using a very bright nanosecond neutron flash from DPF devices.

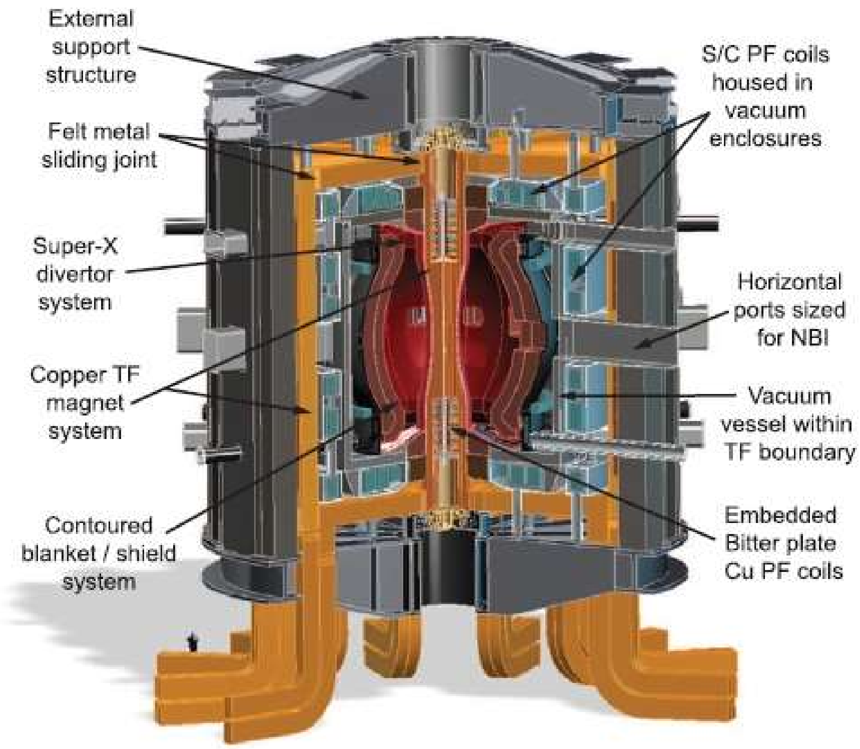

FIG. 3. General arrangement for ST–FNSF showing TF and PF magnets, blanket modules, vacuum vessel, and external support structures [1].

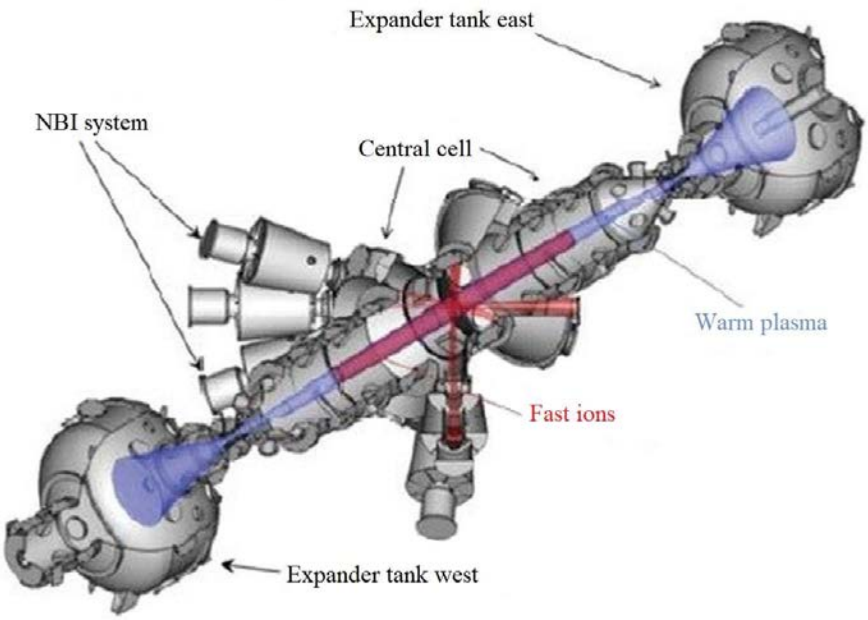

FIG. 4. The layout of GDT experiment [2].

3.2.2. Optimization of design points

Plasma conditions for neutron production were optimized for all CFNS concepts. The results can be summarized as follows:

- Parameter space were explored for the FNS–ST (Fig. 5) and DEMO–FNS (Fig. 6) by Kurchatov Institute (Russian Federation) corresponding to Q = 0.3–1, with First wall and Divertor loading less than 10 MW/m^2. The University of Texas–Austin (USA) team examined a variety of scenarios, focusing on the effects of the shape of the divertor.
- Tokamak Energy (UK) explored the operational space for both for current ramp (examining both merging compression and double null merging schemes) and for current flat-top with different heating scenarios and transport assumptions.
- A fundamental requirement for an FNSF is achievement of neutron wall loading of at least 1 MW/m^2 while providing sufficient component testing area 10 m^2. Based on previous design studies and calculations performed during these studies, the lower-bound on device size capable of meeting these neutron flux and testing area goals is R0 ~ 1 m.
- Woodruff Scientific (USA) examined profile effects on performance for the spheromak compression concept, as well as the role of plasma shaping on pressure stability.
- University of Uppsala (Sweden) optimized plasma parameters and the parameters of Straight Mirror neutron source (and hybrid) for maximum efficiency, within the scheme of deuterium bulk plasma and tritium hot minority.
- Institute of Nuclear Energy Safety Technology (China) examined the use of Electron Cyclotron Resonance Heating (ECRH) to increase the electron temperature and reduce the neutral beam injection power required to heat and sustain the warm plasma in the GDT concept; further, a method was investigated that the neutral beam obliquely injected at high magnetic field position rather than at middle plane, which is aimed at improving the fusion energy gain (Q) of GDT based fusion neutron source.

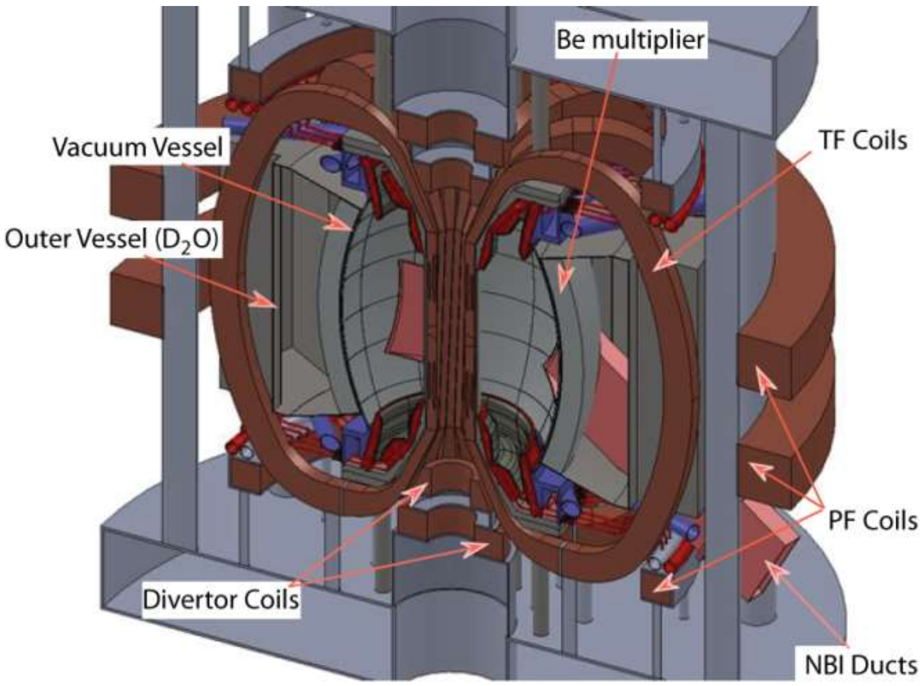

FIG. 5. FNS–ST cut-away view.

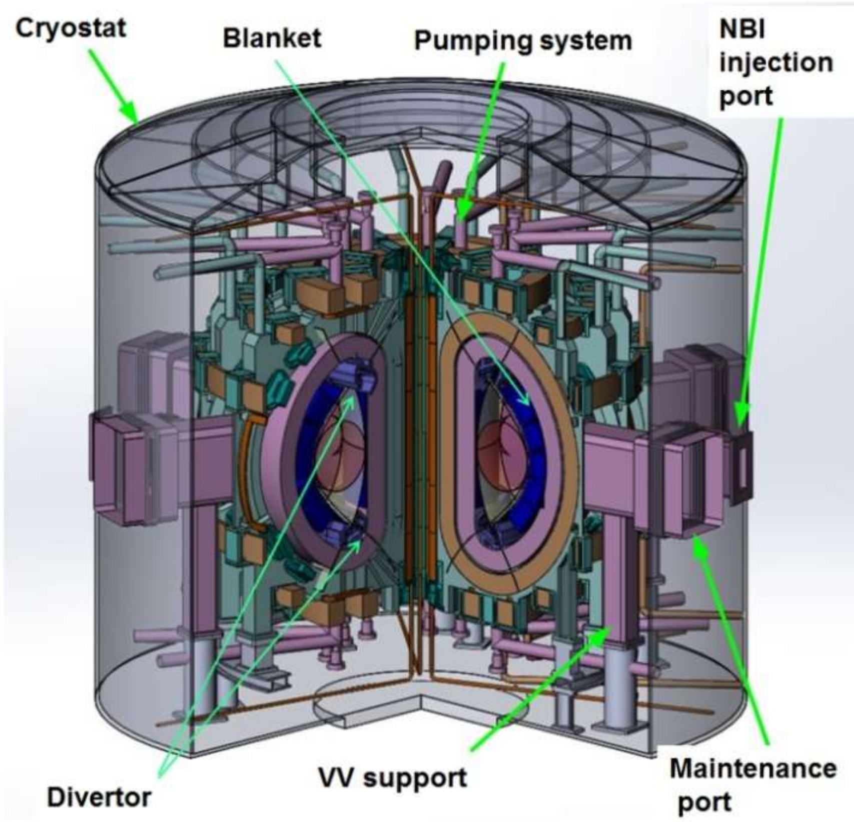

FIG. 6. Cut-away view of DEMO–FNS tokamak.

3.2.3. Enabling technologies

Validated technologies for CFNS include magnets, vacuum vessel, first wall materials, power systems and diagnostics. Progress was made in validated technologies by those groups with experimental programmes. The results can be summarized as follows:

- For ST devices, suitable choices of materials were identified. In particular, reduction to 0.2 MW/m^2 neutron loading allowed to use austenitic steel as structural materials; ceramic insulators (spinel – Al_2MgO_4, CaO) were compatible with neutron environment; polyimide insulation was appropriate in combination with the sufficient radiation shielding less than 0.05 W/cm^3. For the magnets, CuCrZr-bronze for ST-tokamak without shielding was preferable. Considerations were also made for superconductors in two versions for the toroidal field coils.
- With the baseline shielding and breeding requirements chosen for FNFS, scaling studies found that a plasma major radius of R_0 = 3 m can achieve both peak neutron fluences of at least 5–6 MWy/m^2 and also Q_{eng} ~ 1 for a wide range of aspect ratios and confinement assumptions.
- Technologies for a thin first wall and divertor operation at 10 MW/m^2 were investigated. Further considerations were made on material and structure of vacuum vessel. NBI and divertor arrangements were analyzed, including design of advanced divertors to be installed and tested in several devices. A double null magnetic configuration was considered for the spherical and conventional tokamaks. Be tiles and Li-injection were chosen to provide mono-material first wall and to reduce erosion by fast alphas.

- High Temperature Superconductors (HTS) offer more compact magnet systems as compared to conventional low temperature superconductors (LTS). Several magnetic fusion devices were used as testbeds for HTS coils in fusion environment: At the tokamaks GOLEM (Czech Technical University in Prague, Czech Republic), ST–25 (Tokamak Energy, UK) and ST–25 HTS (Tokamak Energy, UK), the use of HTS in magnets was tested for the first time on fusion devices. The set of validated technologies include: (i) design, manufacture and tests of cryostats for HTS magnets and HTS coil feeds, (ii) studies of properties of HTS (critical current dependence on magnetic field, temperature and current quench characteristics), (iii) tests of HTS magnets on GOLEM and ST–25, (iv) operation of ST–25 HTS with a complete set of HTS coils up to 29 hours.
- In addition, HTS poloidal field coils for the GLAST–3 tokamak (National Tokamak Fusion program, Islamabad, Pakistan) were designed and constructed in collaboration with Tokamak Energy (UK).
- Integration of tokamak, hybrid blanket and nuclear fuel cycle technologies were carried out at a conceptual level by NRC Kurchatov (Russian Federation). Methods for tritium breeding, minor actinide burning, implementation of Th–U nuclear fuel cycle were identified. The results were taken into account in the choices for materials and components for test module blankets.
- NBI technology developed in Russia is a base for a validated plasma heating technology, but longer pulses are required for steady-state operation. NBI injection with positive ion source can be used for a spherical tokamak (120 keV) while a negative ion source can be used for conventional tokamak (500 keV). Pumping is provided by cryo-pumps and forepumps. Cooling system uses light water H_2O as major coolant. Blankets may have D_2O coolant with an option for molten salt coolants. ITER technologies could be applicable for the FNS tritium plant. Evaluations of options for the NB fueling were performed by Budker (Russian Federation) in a super compact fusion neutron source, including tritium fueling and associated issues.
- A minimal set of diagnostics aimed for steady-state operation was formulated. The remote handling systems are still only at a preliminary design stage. A modular design with 6 sectors was developed for the DEMO–FNS project by NRC Kurchatov (Russian Federation).
- A mock-up of the tokamak divertor for high power loads utilizing floating liquid Li technology was designed and fabricated by IPUL (Latvia).
- Some validated technologies were used for the mirror and mirror–stellarator concepts. In stellarator–mirror and SFLM neutron sources and hybrids, due to localization of neutron flux at the mirror section of the device where no sensitive equipment will be present, existing technologies, equipment and materials can be used. The major validated technologies used are radio-frequency heating, neutral beam injection, electron cyclotron plasma production, plasma fueling with gas puff and pellet injection and the steady-state magnetic field with cryogenic coils.
- Institute of Nuclear Energy Safety Technology (China) developed technologies for high temperature superconducting magnets, where one intended goal was for the development of axisymmetric GDT devices.
- For the dense plasma focus, a method was elaborated by A. A. Baikov Institute (Russian Federation) for characterization of the fusion facility as an absorber–scatterer of fusion neutrons by using a very bright nanosecond neutron flash from the dense plasma focus device and a simulator of the neutron fields. The impact from construction elements and environment on the neutron fields around the simulator (a large-scale discharge chamber

of the PF–1000 facility) was deduced from experiments supported by a number of MCNP computations.

- IPPLM (PL) and A. A. Baikov Institute (Russian Federation) determined a method of a considerable decrease of tritium consumption in future 10^{16}—10^{17} neutron sources based on Dense Plasma Focus (DPF). It was proposed and successfully tested in one of the biggest DPF device (the PF–1000U at IPPLM).

3.2.4. Validated modeling

Validated codes were used to simulate the dynamics of plasma-material interaction as well as the response of the materials to heat and particle loads for most concepts in the CRP. The resuls can be summarized as follows:

- The NRC Kurchatov Institute (Russian Federation) performed extensive simulations of the plasma-material interaction. In the scope of development of the computational tools for the design studies of FNS, the Tokamak System code was written; simulation tools for evaluation of radiation effects in materials and tritium transport and for analysis of hydrogen diffusion in structural materials were developed; a tokamak fuel cycle code was developed and applied for estimating the tritium storage, throughput and fuelling rates; a neutron spectra code for beam–plasma interaction was developed; a code for neutronics simulations for neutron flows, nuclear reactions for breeding, transmutation and energy production was developed and applied to the design of FNS–ST and DEMO–FNS; and models for P&T (Processing and Transmutation) have been created.
- Tokamak Energy (UK) developed and used many computation codes and tools. For equilibrium analysis and reconstruction, FIESTA (UK), EFIT (USA) and CCS (Japan) were used. For scenario simulations CORSICA (USA/EU) and DINA (Russian Federation) were used. For stability analysis, MISHKA (EU/Russian Federation), KINKS (Russian Federation), RZIP (EU), PEST (USA), VST (USA) were used. For transport simulations and fast particles ASTRA (Russian Federation), TRANSP (USA), NUBEAM (USA), ASCOT (EU), FIFPS (USA/EU), NFREYA (USA/EU), HAGIS (EU) were used. ANSYS and OPERA (EU) were used for engineering simulations. Aspects of the plasma-material interactions were investigated using SOLPS (EU), MCNP (USA) and FISPACT (EU) codes.
- Woodruff Scientific (USA) developed device models for the CORSICA code for vessel and coil design, stability and transport and the code was applied for design of scenario of ST40 and spheromak compression (SPHEX–FNS). The dynamics of plasma-materials interaction was modeled with MHD tool NIMROD, which allows the heat fluxes onto surfaces to be computed. Interaction of structures with emitted neutrons was calculated with the MCNP6 Monte-Carlo neutron analysis code.
- The University of Texas–Austin (USA) used equilibrium codes CORSICA and VMEC, that were combined and used for modelling. The plasma edge was modeled by SOLPS, and the gyrokinetic code GENE was used for design studies of a compact FNS: SOLPS code was used for investigating the divertor region; spreading of heat flux, developing scenarios for stable detachment; and GENE code was used for investigating of the transport (both particle and thermal) for producing 100MW of fusion power with optimized confinement and divertor. A 2D kinetic code for trapped ions, 2D radio-frequency field simulation code and 0D isotope balance evolution code were developed. Computations for the plasma, coil design and neutrons were fitted to each other as a combined tool for the development of a CFNS. The MCNP6 code was used in numerical calculations.

- At the Institute of Nuclear Energy Safety Technology (China), several codes were exercised. The SYSCODE was developed and updated to calculate GDT plasma parameters. The integrated multi-functional CAD-based SuperMC was used for the numerical simulation and the performance analysis of the FDS–GDT3 fission blanket.
- The IPPLM (Poland) developed a 2D MHD model with Braginskii transport coefficients, with Saha equation for ionization to model the important sheath region at the plasma-material interface.
- A. A. Baikov Institute (Russian Federation) used the MCNP–5 code to model results of experiments on DPF, including distortions produced by elements of the DPF device, its environment and by different parts of a simulator of a Nuclear Fusion Chamber and to characterize field of neutron penetration through a chamber wall.

3.2.5. Safety considerations

For all CFNS designs, safety analysis of accidents was performed. The results can be summarized as follows:

- For tokamak based CFNS, preliminary safety analysis of tokamak complex was performed by NRC Kurchatov Institute (Russian Federation). The radiative-heating power was evaluated for the first wall, the blanket and the divertor materials; Be-recirculation analysis was performed; problems of waste processing and structural materials recycling were identified.
- Safety analysis of the prototype of a compact FNS ST40 was performed by Tokamak Energy (UK) and resulted in implementation in the PPS (Personal Protection System) of the device.
- For stellarator–mirror hybrid, developed by KhiPt (Ukraine), endurance against LOCA and LOFA events was provided by proper choice of the effective neutron multiplication factor for the device. A vertical orientation was considered for the SFLM, developed by Uppsala University (Sweden), to arrange passive circulation for removal of decay heat in case of an emergency shut-down.
- For GDT CFNS, developed by Institute of Nuclear Energy Safety Technology (China), the shielding of high flux fast neutron and potential tritium inventory were the key issues of nuclear safety. A 3D neutronics model was developed, and the shielding performance was calculated using SuperMC. The result showed a total neutron of $10^{22}/m^2$ in the lifetime that meets the safety requirement. The public early dose was evaluated due to unit gram tritium, activated dust, activated corrosion products and activated gases accidental release into environment, which indicated the priority of radiation protection for FNS device. A comprehensive safety analysis of GDT CFNS (including source terms, ORE, accident transient, environment impact, etc.) was found to be necessary.
- For Plasma Focus based CFNS, an analysis of radiation hazards for the operating staff (connected with activation of the neutron generator elements) was performed by IPPLM (Poland). Using advanced equipment for precise low-dose activation measurements, an estimate was made for the expected hazard to the operating staff (during operation of the generator and maintenance periods). Especially for the more hazardous scaled-up neutron intensity/energy systems, appropriate recommendations for technical and organizational management were elaborated.

4. CONCLUSIONS

This publication provides conceptual and engineering design parameters (e.g. methodologies, tools, data, technologies and knowledge) for compact fusion neutron sources targeting steady state operation in the range of power 1–100 MW, for the fusion energy multiplication factor 0.1 < Q < 1, and for neutron rates of the other 10^{17}–10^{19} n/s.

In particular, it confirmes the leading role of tokamaks (see supplementary files reports 1–3) and clarifies the role and opportunities of dense plasma foci (see supplementary files report 4) and open systems (see supplementary files reports 5–7), and compact tori (see supplementary files report 8).

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LIST OF ABBREVIATIONS

CFNS	compact fusion neutron source
DEMO	demonstration fusion power plant
DPF	dense plasma focus
FNS	fusion neutron source
FNSF	fusion nuclear science facility
GDT	gas dynamic trap
HTS	high temperature superconductor
IFMIF	international fusion materials irradiation facility
LOCA	loss of coolant accident
LOFA	loss of flow accident
LTS	low temperature superconductor
MCNP	monte carlo n-particle
MHD	magneto hydro dynamic
PF	plasma focus
PPS	personal protection system
SFLM	straight field line mirror
SOL	scrape-off layer
ST	spherical tokamak
SuperMC	super monte carlo calculation program for nuclear and radiation process
SYSCODE	system analysis program for parameters optimization and economic assessment of fusion reactor

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Research Coordination Meetings

Vienna, Austria: 14–16 November 2012, 10–12 November 2014, 22–25 November 2016

Consultancy Meetings

Vienna, Austria: 23–25 January 2017

Annex

SUPPLEMENTARY FILES

The supplementary files for this publication can be found on the publication's individual web page at www.iaea.org/publications.

Development of Tokamak based fusion neutron soruces and fusion-fission hybrid systems *B.V. Kuteev*
Increased heat dissipation with the X-divertor geometry facilitating detachment onset at lower density in DIII-D *B. Covele, M. Kotschenreuther, S. Mahajan, P. Valanju, A. Leonard, J. Watkins, M. Makowski, M. Fenstermacher*
Fusion nuclear science facilities and pilot plants based on the spherical tokamak *J.E. Menard, T. Brown, L. El-guebaly, M. Boyer, J. Canik. B. Colling, r. Raman, Z. Wang, Y. Zhai, P. Buxton, B. Covele, C. D'Angelo, A. Davis, S. Gerhardt, M. Gryaznecich, M. Harb, T.C. Hender, S. Kaye, D. Kingham, M. Kotschenreuther, S. Manajan, R. Maingi, E. Marriott, E.T. Meier, L. Mynsberge, C. Neumeyer, M. Ono, J.-K. Park, S.A. Sabbagh, V. Soukhanovskii, P. Valanju, R. Woolley*
Conceptual development of a compact neutron source based on plasma-focus *R. Miklaszewski, M. Paduch, A. Kasperczuk, S. Jednorog*
Study of magnetic mirror and stellarator based concepts of fusion neutron sources *V.E. Moiseenko, O. Agren, K. Noack, S.V. Chernitskiy, V.G. Kotenko, A. Hagnestal, V.V. Nemov, Y.S. Kulyk, A.V. Lozin*
Conceptual design of steady-state compact fusion neutron sources based on gas dynamic trap *Y. Wu, D. Chen, Q. Zeng, C. Lian, M. Ni, M. Wang, J. Jiang*
Mirror based fusion neutron source: status and prospective *A.V. Anikeev, P.A. Bagryanky, A.D. Beklemishev, A.V. Burdakov, A.A. Ivanov, E. Yu. Kolesnikov, S.V. Murakhtin, V.V. Prikhodko, A.L. Solomakhin, D.V. Yakovlev, D.V. Yurov*
Adiabatic compression of a compact torus *S. Woodruff, J.E. Stuber, C. Bowman, P.E. Sieck, P.A. Melnik, C.A. Romero-Talamas, J.B. O'Bryan, R.L. Miller*

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