Design status of the DEMO-FNS Steady State Tokamak in RF

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Collaborators: Efremov Institute, Dollezhal Institute, AtomProject, Bochvar Institute, Polytechnic University, CTF-Centre

B.V. Kuteev et al., IAEA SSO-8, 26-29 May 2015, Nara, Japan
DEMO-FNS background

• DEMO-FNS tokamak device is the key facility in the hybrid branch of the Russian fusion program.
• The construction of DEMO-FNS is planned by 2023. This facility should provide the choice of steady state operation regimes, tests of materials and components, demonstration of tokamak enabling technologies and molten salt nuclear technologies of hybrid blanket and radiochemical plant for Pilot Hybrid Plant (PHP).
• The PHP construction is planned by 2030. Design targets are 40 MW for the fusion power, 500 MW for the total thermal power and 200 MW for the electric power that should provide engineering $Q_{eng} \sim 1$ (self-sufficiency).
Strategy 2013 for Fusion-Fission development in Russia

E. Velikhov, IAEA FEC-25, O-3
B.Kuteev et al. NF, 55 (2015) accepted

Burning Plasma Physics

T-15 ➔ ITER ➔ DEMO ➔ PROTO

Nuclear physics and technology

DEMO-FNS ➔ PHP

Test beds for enabling technologies

Test beds for molten salt technologies

2015 ➔ 2030 ➔ 2050

Hybrid ➔ Fusion

Nuclear technologies of new generation
Major facilities on the path to Industrial Hybrid Plant

SSO&MS
Steady State Technologies
• Magnetic system
• Vacuum chamber
• Divertor
• Blanket
• Remote handling
• Heating and current drive
• Fuelling and pumping
• Diagnostics
• Safety
• Molten salts

Globus-M3

FNS-ST
DT neutrons

DEMO-FNS
MS blankets

• Integration
• Materials
• Hybrid Tech

Pilot Hybrid Plant construction by 2030
P=500 MWt, \( Q_{\text{eng}} \sim 1 \)

Industrial Hybrid Plant construction by 2040
P=3 GWt, \( Q_{\text{eng}} \sim 6.5 \)
P=1.3 GWe, P=1.1 GWn, MA=1t/a, FN=1.1 t/a
Feasibility of Pilot Hybrid Reactor by 2030

1. Regimes with $Q \sim 1$ are realized in tokamaks, low BPP impact
2. Electron temperature sufficient for DT beam driven fusion $T = \sim 4$ keV has been demonstrated in numerous experiments
3. Non-inductive current drive was demonstrated in conventional tokamaks and is close to demonstration in spherical machines
4. Reduction of technical requirements on neutron loading in PHP to 0.2 MW/m² and fluence value for operation time below 2 MWy/m² allows to use commercially available materials
5. Economics of PHP is acceptable in case of total products selling: MA incineration, electricity production, tritium breeding, fuel breeding for U-Pu and Th-U nuclear fuel cycles.
6. System models and codes predict appropriate parameters of PHP
7. Russia has an appropriate cooperation of fusion and fission organizations and well qualified staff
Construction Risks for Pilot Hybrid Plant

1. Low design level for Hybrid systems (conceptual or pre-conceptual)
2. Enabling Technologies for tokamak Steady State Operation need substantial resource upgrade (from minutes to ~5000 hours)
3. Additional R@D are mandatory for fusion nuclear science and technology
4. Molten salt nuclear technology of hybrid blanket and radio-chemical system require demonstration
5. Lack of information on tokamak operation under high plasma loadings, noninductive current drive and non-equilibrium plasmas
6. Poor database on radiation damage of materials in 14 MeV neutron spectra
7. Challenging choice of materials and molten salt compositions is foreseen
8. Licensing delays and Atomic Energy Law update
### Structural and Functional Materials of the Hybrid Concept

<table>
<thead>
<tr>
<th>Structural materials:</th>
<th>Functional materials:</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>austenitic steels</em></td>
<td>Be</td>
</tr>
<tr>
<td>12X18H10T (SS316)</td>
<td><em>Li$_4$SiO$_4$</em></td>
</tr>
<tr>
<td>ЧС-68</td>
<td><em>T</em></td>
</tr>
<tr>
<td>ЭК-164</td>
<td></td>
</tr>
<tr>
<td>Nickel alloys</td>
<td></td>
</tr>
<tr>
<td>Hastelloy</td>
<td></td>
</tr>
<tr>
<td>Vanadium alloys</td>
<td></td>
</tr>
<tr>
<td>V-(4-9)Cr-(0.1-8)W-(1-2Zr)</td>
<td></td>
</tr>
<tr>
<td>V-4Cr-4Ti</td>
<td></td>
</tr>
</tbody>
</table>

#### Materials for Magnetic System
- Cu
- CuCrZr
- Nb$_3$Sn
- NbTi
- MgB$_2$

#### Insulators
- MgAl$_2$O$_4$
## Require Q for hybrids

Recirculating power fraction = 0.2, $P_{\text{nuclear}} = 3000\text{MW}$

<table>
<thead>
<tr>
<th>Actinide burner</th>
<th>Minimum Q required</th>
<th>$P_{\text{fusion}}$, MW</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transuranics, $M=19$</td>
<td>1</td>
<td>200</td>
<td>solid fuel, engineered or active safety</td>
</tr>
<tr>
<td>Minor actinides, $M=38$ to 150</td>
<td>1 to 0.5</td>
<td>25 to 100</td>
<td>solid fuel, engineered or active safety</td>
</tr>
<tr>
<td></td>
<td>0.2 av.</td>
<td>50 av.</td>
<td></td>
</tr>
<tr>
<td>Transuranics, Molten salt, $M=13$</td>
<td>1.5</td>
<td>280</td>
<td>passive safety</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel producer</th>
<th>$M=2.1$, $^{233}\text{U}$</th>
<th></th>
<th>passive safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission-suppressed, $M=10$, $^{239}\text{Pu}$</td>
<td>2</td>
<td>370</td>
<td>engineered safety</td>
</tr>
</tbody>
</table>

| Power producer | $M=10$ | 2 | 370 | molten salt-passive safety |

| Pure fusion | $M=1.34$ | 11 | 2300 | solid fuel-engineered safety |

Comments: passive safety
DEMO-FNS Features

- DEMO-FNS has a superconducting magnetic system utilizing low temperature superconductors Nb$_3$Sn and NbTi.
- The steady state operating device has the major radius $R = 2.5$-$2.7$ m and the minor radius $a = 1$ m, toroidal magnetic field $B = 5$ T, plasma current $I_p = 5$ MA, neutral beam heating and current drive system with the total power of 30 MW and 6 MW of gyrotron power at 170 GHz.
Parameters of DEMO-FNS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, m</td>
<td>2.7</td>
</tr>
<tr>
<td>R/a</td>
<td>2.7</td>
</tr>
<tr>
<td>κ</td>
<td>2.1</td>
</tr>
<tr>
<td>δ</td>
<td>0.5</td>
</tr>
<tr>
<td>I_p, MA</td>
<td>5.0</td>
</tr>
<tr>
<td>B_T, T</td>
<td>5.0</td>
</tr>
<tr>
<td>n, 10^{20} m^{-3}</td>
<td>1.0</td>
</tr>
<tr>
<td>P_n/S, MW/m^2</td>
<td>0.2</td>
</tr>
<tr>
<td>E_b, keV</td>
<td>500</td>
</tr>
<tr>
<td>P_b, MW</td>
<td>30</td>
</tr>
<tr>
<td>Angle NBI, deg</td>
<td>0</td>
</tr>
<tr>
<td>P_EC, MW</td>
<td>6</td>
</tr>
<tr>
<td>H-factor</td>
<td>1.0</td>
</tr>
<tr>
<td>β_N</td>
<td>&lt;3</td>
</tr>
<tr>
<td>f_non-ind</td>
<td>1.0</td>
</tr>
<tr>
<td>P_{diss, TF}, MW</td>
<td>10</td>
</tr>
<tr>
<td>P_{diss, PF}, MW</td>
<td>5.0</td>
</tr>
<tr>
<td>S_{wall}, m^2</td>
<td>188</td>
</tr>
<tr>
<td>V_{pl}, m^3</td>
<td>113</td>
</tr>
</tbody>
</table>

Demonstration
- Tritium breeding
- MA incineration
- Fissile nuclide production
- Destruction of long life radionuclides
- Heat transfer
## FNS-ST, DEMO-FNS and ITER parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FNS-ST</th>
<th>DEMO-FNS</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius $R$, m</td>
<td>0.5</td>
<td>2.75</td>
<td>6.2</td>
</tr>
<tr>
<td>DT-fusion option</td>
<td>Beam driven fusion</td>
<td>Beam driven and thermonuclear fusion</td>
<td>Thermonuclear fusion</td>
</tr>
<tr>
<td>Heat transfer from alphas to plasma</td>
<td>no</td>
<td>yes small</td>
<td>yes BPP valuable</td>
</tr>
<tr>
<td>Divertor configuration</td>
<td>DN</td>
<td>DN</td>
<td>SN</td>
</tr>
<tr>
<td>Toroidal field at the VV center, T</td>
<td>1.5</td>
<td>5</td>
<td>5.3</td>
</tr>
<tr>
<td>Fusion power, MW</td>
<td>1 - 3</td>
<td>30 - 40</td>
<td>500</td>
</tr>
<tr>
<td>Auxiliary heating power $P_{\text{AUX}}$, MW</td>
<td>$\sim 8 - 10$</td>
<td>30 - 40</td>
<td>50 - 70</td>
</tr>
<tr>
<td>Fusion energy gain factor $Q$</td>
<td>$\sim 0.2$</td>
<td>$\sim 1$</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>Shielding at high field side, m</td>
<td>Без защиты</td>
<td>$\sim 50$ cm</td>
<td>60 – 80cm</td>
</tr>
<tr>
<td>Type of magnetic system</td>
<td>CuCrZr</td>
<td>LTS</td>
<td>LTS</td>
</tr>
<tr>
<td>Neutron loading $\Gamma_n$, MW/m²</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Neutron fluence at lifetime, MWy/m²</td>
<td>$\sim 2\ (*)$</td>
<td>$\sim 2$</td>
<td>0.3</td>
</tr>
</tbody>
</table>
DEMO-FNS Map of physical parameters

Physical assumptions are moderate
DEMO-FNS Basic plasma configuration

Steady State free boundary equilibrium magnetic configuration
Breakdown in DEMO-FNS

\[ \Phi_0 \approx 10 \text{ Vs} \]
\[ B_{Z_{\text{max}}} \approx 12 \text{ T} \]
Current and fusion power in DEMO-FNS

Current and its components versus plasma density

Fusion power and components (beam plasma fusion + thermonuclear) versus plasma density

System codes suggest reaching design parameters of DEMO-FNS and the neutron loading that is higher than 0.2 MW/m²
DEMOf-NS magnet system details

• The magnetic coil system consists of 18 toroidal coils, 12 poloidal coils, 2 vertical control coils and 18 RMP correcting coils

• The partitioned central solenoid (CS) has the flux storage of 8 Wb increased by poloidal coils up to 20 Wb that is sufficient for plasma formation and the current rump up to 5 MA during 2 seconds

• Peripheral parts of the CS are used for shaping the magnetic configuration
Toroidal field coils

Number of toroidal field coils \( N_{TF} = 18 \)
Two loops \( \text{Nb}_3\text{Sn}+\text{NbTi} \)
Total TFC current \( I_{TF} = 70 \text{ MA-turns} \)
TFC magnetic energy \( W_{TF} = 6 \text{ GJ} \)
DEMO-FNS Poloidal magnetic system

PF coils

CS

DEMO-TIN cross section. Position of passive (PC1) and active (AC) control coils is shown.

Two variants of passive stabilisation coils with 2 (left) and 24 (right) frames
General layout of DEMO-FNS

TF coil cross section

Equatorial section of DEMO-FNS
Radial structure of DEMO-FNS
DEMO-FNS vacuum vessel details

- The vacuum vessel (VV) is made of austenitic stainless steel (SS) with the shell thickness of 3 cm and the 2 cm bulkheads (ribs)
- The volume of the VV is filled with 70% SS and 30 % water for neutron&gamma shielding
- The VV thickness is 50 cm at the high field side (HFS) and 60 cm at the LFS and divertor regions
- The VV acts as a radiation shield of the magnetic system reducing the radiation heating below 1 mW/cm$^{-3}$
DEMO-FNS  Vacuum vessel (VV)

VV sector (inside)

VV sector (outside)

Blanket segmentation

Shield between two shells of VV
Electronic mockup of VV

Distribution of EM pressure for upward disruption accident

VV shell

VV ribs

VV shell under 40 bars of internal pressure
VV cooling system

Heat exchanger 1

Heat exchanger 2

Pump1

Circuit1

Pump2

Circuit2

Neutron shield unit

VV shell

VV structure at high field side

Input collector

Neutron shield unit

Temperature fields under normal operation
DEMO-FNS divertor details

• The divertor has a double null magnetic configuration with a strong shaping (δ up to 0.5) and long outer legs (L~0.5R)
• Divertor is capable of operating under heat loading up to 10 MW/m²
• Lithium technologies including dust injection are used for the edge plasma control and protection of the plasma facing components from erosion
• Remote handling concept assumes repair procedures and changing the divertor cassettes through equatorial ports
Engineering design of the first wall and vacuum vessel, magnet system, divertor, fuel cycle for DEMO-FNS tokamak

In 2014 mockups were manufactured and tested of:
- First wall
- Divertor plate
- Magnetic diagnostic system
- Lithium injection system

Concepts of hybrid blanket (fuel, incineration, energy), diagnostic complex, remote handling will be considered and formulated
Divertor plates

Procedure of divertor module removing through equatorial port

See in more details I.V. Mazul presentation In-vessel components development from ITER to DEMO, IAEA DEMO-3 technical meeting, Hefei, China
DEMO-FNS blanket details

• The tokamak design reserves a place for hybrid blankets of different styles with 76 cm thickness and 4 m height at the low field equatorial zone.
• Energy production, fissile nuclide and tritium breeding, transmutation technologies should be demonstrated by hybrid blankets.
• Molten salts will be tested as the basic option for fuel mixture and coolant (now H₂O is first).
• The blanket modules are replaceable.
• Blanket module maintenance is fulfilled using transfer in the major radial direction through 6 equatorial ports (toroidal shifts for CB neighbors).
Blanket: 24 sections of different functions

- processing of wasted nuclear fuel;
- tritium breeding;
- sections for U-blanket testing;
- sections with ports for arrangement of plasma auxiliary heating testing (antennas and waveguides for high-frequency systems and elements of NBI beam ducts);
- diagnostical equipment.

Each section includes stationary part (iron-water shield) and removing part. Vacuum boundary is formed on surface of stationary shield.
Two fuel cycles considered with molten salt blankets

**U-Pu**

- 1Pu+1T per 1n(DT)

**Th-U**

- 0.6U+1T per 1n(DT)
DEMO-FNS heating system details

• Plasma heating and current drive is provided by 6 injectors with the unit power of 7.5 MW each and the neutral energy of up to 500 keV
• In operating conditions four of them are in the active mode, one is sequentially regenerated and one is in reserve for the ion source exchange and maintenance procedures
• Injectors operate on a 50:50 mixture of deuterium and tritium /Option of operating on D only is explored as well that reduces the tritium inventory
• Six gyrotrons have the power of 1 MW each and the frequency of 170 GHz. There is also a reserve channel to support maintenance and scheduled repairs during the device operation.
The DEMO-FNS is equipped with a large scale fuelling system with deuterium-tritium mixture. The gas injection rate may reach $10^{23}$ atoms per second. The mixture composition 50:50 percent is maintained by cleaning out impurities including helium and balancing the losses of deuterium and tritium caused by the fusion reactions. High vacuum pumping from divertor of the device is provided by cryogenic pumps with sequential regeneration (up to 24 vertical ports).
DEMO-FNS safety & radiochemical systems

• The facility is equipped with detritiation systems for water and gases. The total tritium amount on site is evaluated as ~2 kg during the operation campaign. Less than 100 grams are expected in the vacuum vessel.

• Radiochemical plant supports preparation of the molten salt mixture, technological procedures for the nuclides feeding and extraction in continuous regime and their utilization.

• The molten salts are used as nuclear fuel mixtures and the first loop coolants on the site.

• The technologies for tritium breeding and extraction will be developed within DEMO-FNS project.
1 – divertor pump; 2 – NBI pump; 3 – VV&FW; 4 - blanket; 5 – membrane purification system; 6 – T-bed; 7 - Hydrogen compounds catalytic decomposition system; 8 – Super-heavy water waste recycling system; 9 - Hydrogen isotopes separation system; 10 - Gas puff system; 11 - Pellet-injection system; 12 - NBI system; 14 – plasma
**Tritium technologies: optimization**

code “TC-FNS” was developed to estimate the distribution of tritium in the systems of a fusion facility and elements of "tritium plant”.

Use of fuel ratio of the mixture to 50% D-50% T for all systems

H-isotope separation system is required for protium removal only → a smaller amount of tritium on site

**But NBI system is the most significant consumer of fuel**

<table>
<thead>
<tr>
<th>FNS system</th>
<th>NBI (D-only), (g)</th>
<th>NBI (D:T=1:1), (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral Beam Injection system</td>
<td>7</td>
<td>44</td>
</tr>
<tr>
<td>Divertor pumping and fuel injector systems</td>
<td>27</td>
<td>17</td>
</tr>
<tr>
<td>Cryotraps and membrane gas purification system</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Hydrogen isotopes long-term storage system (getters)</td>
<td>116</td>
<td>178</td>
</tr>
<tr>
<td>Isotopes separation system</td>
<td>81</td>
<td>198</td>
</tr>
<tr>
<td>Hydrogen compounds catalytic decomposition system</td>
<td>41</td>
<td>100</td>
</tr>
<tr>
<td>Hydrogen isotopes long-term storage system (getters)</td>
<td>92</td>
<td>225</td>
</tr>
<tr>
<td>Recycling of super heavy water waste system</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>Pipelines, receivers, pumps, etc.</td>
<td>0,03</td>
<td>0,03</td>
</tr>
<tr>
<td>Tokamak plasma</td>
<td>1780</td>
<td>1797</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>492</strong></td>
<td><strong>890</strong></td>
</tr>
</tbody>
</table>

tritium burnup, per year
Schematic of DEMO-FNS building (2023)

Demonstration of hybrid technologies

- Tritium breeding,
- Fissile nuclides,
- Incineration of long life radionuclides
- Heat transfer technologies

Fusion power 40 MW
Subcritical fission power up to 500 MW
1. Tokamak building
2. Tritium and fueling building
3. Heating and current drive
4. Diagnostics
5. Hot rooms
6. Low waste
7. Access building
8. Pulse power
9, 10. Magnet power supply
11. Switchers
12. Accumulators
13. NBI power supply
14. Power supplies
15. Emergency power
16. Compressors
17. Cryostates
18. Storage tanks
19. Services
20. Heat exchangers
21. Water pump station
22. Administration
23. Control
24. Radiochemistry
25. Steam power
26. Chemistry
27. Transformers
28. Electric power
29. Distillation
30. Entrance 1
31. Entrance 2
32. Parking

Total site area: 427 m x 670 m = 286,090 m²
The current level of the design corresponds to conceptual one. The engineering design stage will be completed in 2015 for a simplified water coolant option.

We have started manufacturing of mockups for VV, divertor, diagnostics of SS magnetic fields.

This project is realized in collaboration of Kurchatov institute with public corporations NIIIEFA, NIKIET, ATOMPROJECT (VNIPIET), VNIINM, SPb Polytechnic University and CTF-Center.
# Mass of magnets and vacuum vessel

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>mass, ton</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnets</strong></td>
<td></td>
</tr>
<tr>
<td>Toroidal coils (LTS, Cu, insulation, SS-bodies)</td>
<td>770</td>
</tr>
<tr>
<td>Poloidal coils (LTS, Cu, insulation, SS-bodies)</td>
<td>660</td>
</tr>
<tr>
<td>Central solenoid (LTS, Cu, insulation, SS-bodies)</td>
<td>60</td>
</tr>
<tr>
<td>Inter-coil and enforcement structures and supports</td>
<td>130</td>
</tr>
<tr>
<td><strong>Total magnet system</strong></td>
<td>1620</td>
</tr>
<tr>
<td><strong>Vacuum vessel with in-vessel components</strong></td>
<td></td>
</tr>
<tr>
<td>Vacuum vessel</td>
<td>630</td>
</tr>
<tr>
<td>Radiation Shield</td>
<td>1500</td>
</tr>
<tr>
<td>Blanket</td>
<td>500</td>
</tr>
<tr>
<td><strong>Total Vacuum vessel with in-vessel components</strong></td>
<td>2630</td>
</tr>
<tr>
<td><strong>Total MS+VV</strong></td>
<td>4250</td>
</tr>
<tr>
<td><strong>Total Power consumption</strong></td>
<td>150-200 MW</td>
</tr>
<tr>
<td>NBI 100—120 MW, Cryogenics~20 MW, other 30—60 MW.</td>
<td></td>
</tr>
<tr>
<td><strong>Peak power at the initiation stage</strong></td>
<td>~400 MW</td>
</tr>
</tbody>
</table>
Conclusions

• R&D programme and roadmap have been proposed to create Pilot Hybrid Plant (PHP) in Russia on basis of tokamak and molten salt technologies by 2030
• The engineering design of the DEMO-FNS device for demonstration of hybrid and molten salt technologies has been started in collaboration with Rosatom public organizations and universities to be completed in 2015
• Modeling of steady state regimes and scenarios suggest technical feasibility of DEMO-FNS and PHP
• Together with ITER the PHP project is capable to accelerate realization of DEMO programme and make a valuable contribution into creation of Commercial Fusion Power Plant in Russia by 2050
REFERENCES