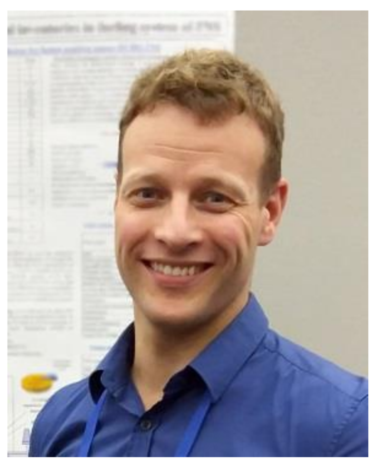

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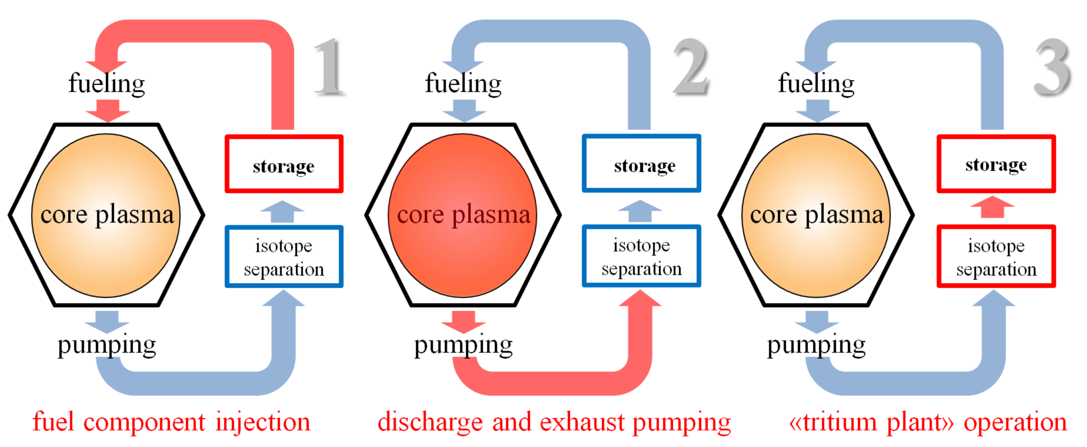
STATUS OF THE DEVELOPMENT OF A TRITIUM FUEL CYCLE FOR LONG-TERM TOKAMAK OPERATION

INTRODUCTION

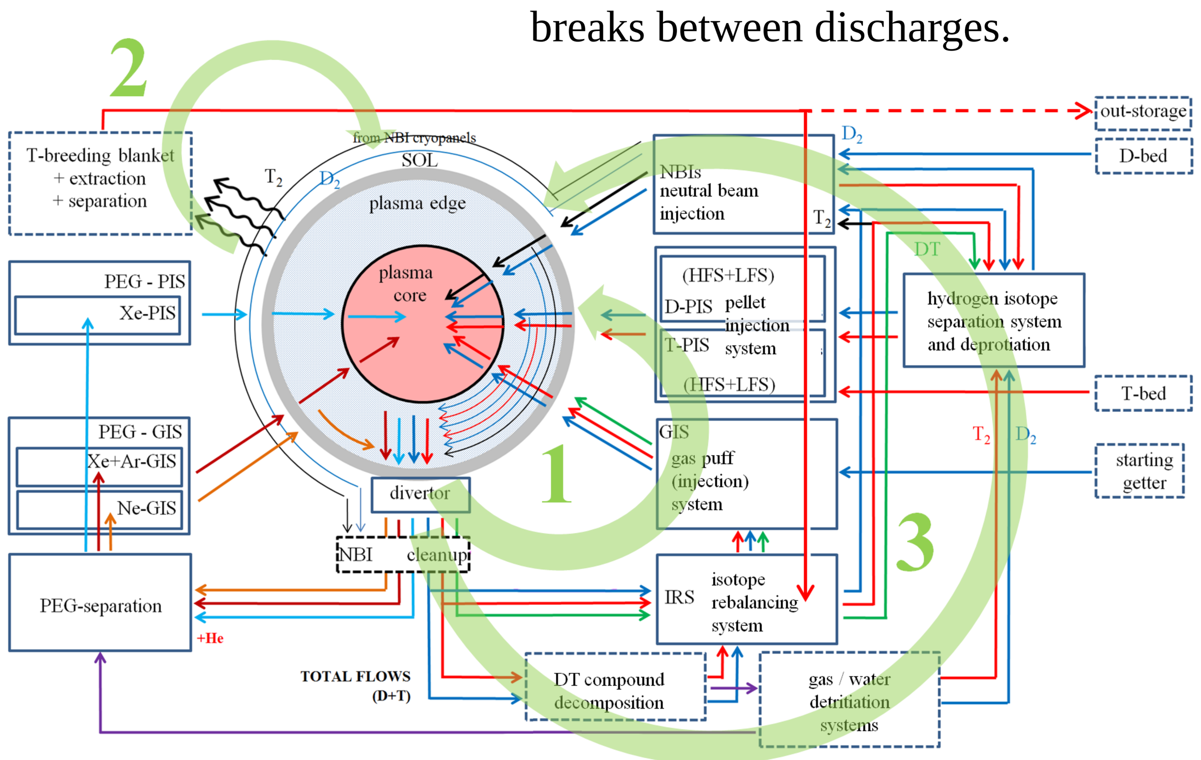
Steady-state fusion reactors will require a fuel cycle design and technology different from the generally accepted one (for experimental facilities), as well as a steady-state mode of all fuel cycle systems to prevent tritium inventories. **Concept of DT - fuel cycle (FC) is developed in RF for tokamak based fusion neutron sources (for projects with fusion power of 3-40 MW).** The fuel cycle design provides fuel injection into plasma with a given isotopic composition and in the required quantity. The proposed design of the fuel cycle for a fusion neutron source ensures the operation of the DEMO-FNS and FNS-ST tokamaks with given values of plasma density and its isotopic composition in a steady-state mode. The SOLPS, ASTRA, and FC-FNS codes are used for interaction of the FC with the plasma of the core and the divertor. **For the candidate fuel cycle technologies selected on the basis of the conducted simulation and analysis, an analysis of the technology readiness levels is carried out. The tritium and deuterium amount calculation in the facility's FC systems was carried out taking into account specific technological solutions.**

BACKGROUND and CHALLENGES

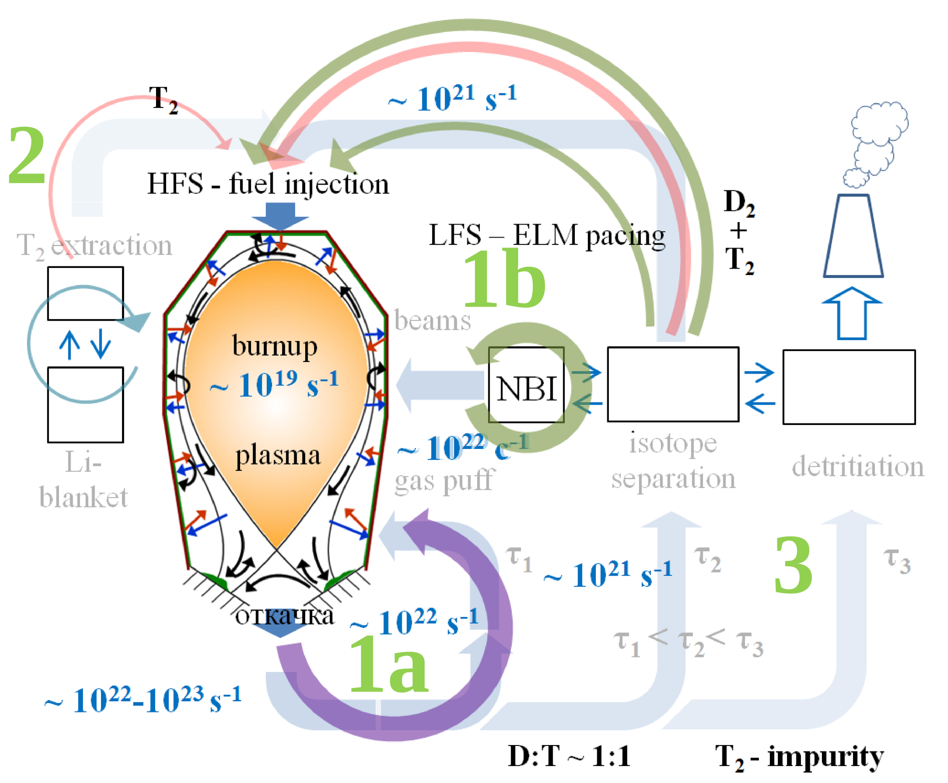


Reactors with long-term discharges requires a fundamentally new approach to the FC design and the use of new technological solutions for its systems, since all facilities currently operating and those being designed have implemented a **pulse-periodic mode** in which the gas mixture is processed during the breaks between discharges.

3 functional circuits:
the first circuit is designed for rapid processing of tokamak exhaust gases and fueling. The second circuit is designed to separate tritium from the reactor Li-blanket (if any). The third circuit is to process tritium-containing waste, as well as to separate tritium from flows (including from the working rooms air in the accident) and to separate auxiliary gases.



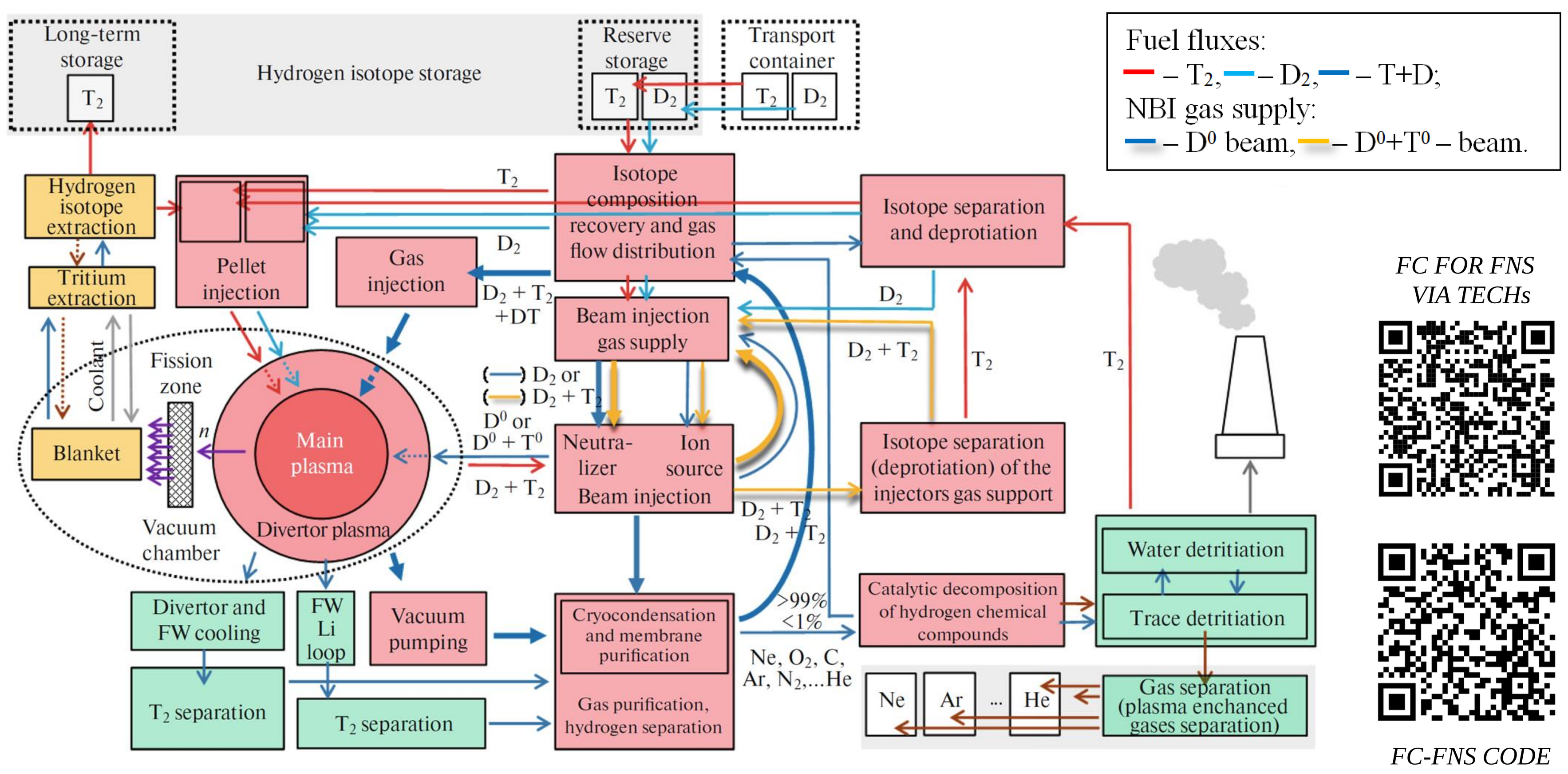
The last circuit is represented by a tritium-containing gas processing system, which combines the processing of gases from the first circuit of the fuel cycle with trace amounts of tritium, as well as emergency processing and cleaning of the atmosphere of rooms and boxes with equipment.



In order to reduce tritium inventories at the facility site, it is advisable to organize several circuits. Flows with a lower tritium fraction should circulate in the loop containing systems with a longer processing time; flows with the highest tritium fraction are processed by systems with a minimum gas residence time. Thus, there is a reduction in flows with a high tritium concentration and a reduction in the processing time.

FC design with **13 gas processing loops** (with different isotopic compositions/tasks, and different technologies) ensures the **min. possible tritium inventory in a steady-state operating facility.**

In all cases, **the flows are stationary, the FC design does not include an operational storage** facility that accumulates gases after their processing and before discharge, and **the FC systems are coordinated in terms of processing time, flows, gas isotopic composition.**



Block diagram of fuel cycle systems.

■ – fast exhaust processing, ■ – tritium extraction from the blanket, ■ – tritium-containing waste processing.

FC FOR FNS VIA TECHs

FC-FNS CODE

The particle **flows in the fuel cycle** are **determined primarily by the requirements for the plasma parameters** provided by the injection systems, as well as by the flows in the pumping system coming from the vacuum vessel to the control systems. The modeling of FC systems and the calculation of the particle flux should be related to the models of core and divertor plasmas.

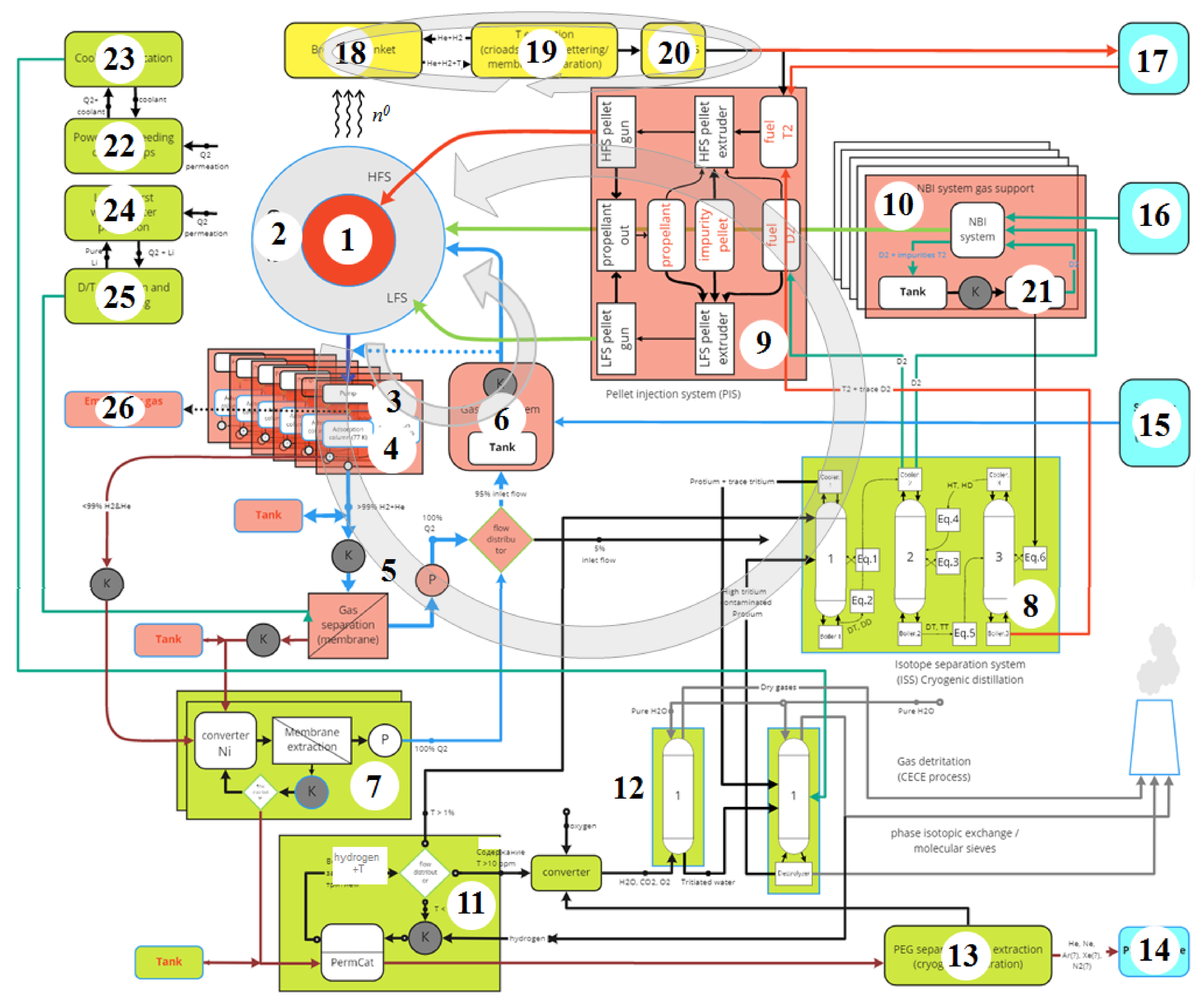
METHODS and MODEL

Modeling of fuel cycle systems with the interaction of the core and divertor plasmas can be implemented using the **SOLPS, ASTRA** and **FC-FNS codes**. The fuel cycle simulation is performed using the FC-FNS code toolkit.

The key difference from similar models is the separate simulation of the D/T fuel components in the fueling and injection systems, core plasma isotopic composition and gas isotopic composition control in the processing systems.

FC-FNS code was created and tested for SSO fusion neutron sources tokamak based in 2013-2025.

By simulation various scenarios of discharge and isotopic composition of the gas mixture in the injection systems and vacuum chamber, the best technological solutions were selected and fuel cycle systems conceptual design was determined.



TRITIUM INVENTORIES IN FC SYSTEMS FOR HEAT BEAM (GAS COMPOSITION) SCENARIOS

Fuel cycle systems	FNS-ST, (g)		DEMO-FNS, (g)		ITER, (g)	EU-DEMO, (g)
	D+T-beam	D / T-beam	*D+T-beam*	D-beam		
Gas puff injection	-	15 / 0	-	45	10	421
Pellet injection		25 / 0		50	45	
Beam injection		1/40		8	1	-
Vacuum vessel and PF components	-	8	-	20	1000 lim	-
Tokamak pumping	*450*	10 / 2	*4500*	60	170	80
Gas separation		1		2	30	6
Hydrogen compounds catal. decomposition	*10*	8 / 1	*100*	10	10	11
NBI system gas composition control	-	1 /2	-	1	-	-
Isotope separation	*40*	22 / 15	*450*	80-150	< 250	550+600
Pipelines, receivers	-	115 / 15	-	70	200	-
Start-up / backup storages	*600 / -*	4 / 2	*5300 / -*	120	< 450	-
Blanket, tritium separation	*2*	2	*130*	2	-	~ 70
Total inventory	***600***	**210 / 90**	***5300***	**500**	**4000**	**1800**

Italics show (for FNS projects) values calculated by "standard" fuel cycle models [*M. Abdou et al*]

Tritium and deuterium inventories in the FC systems were calculated using a computer model of the systems taking into account the technologies used and the design features of the tokamak and technological systems.

The proposed FC design will reduce the tritium reserves required to start the facilities **(less than 0.5 kg for DEMO-FNS/40 MW and less than 0.1 kg for FNS-ST/3 MW)** by almost 10 times compared to the estimates obtained in the DEMO configuration.

READINESS LEVEL analysis of TRITIUM FC TECHNOLOGIES

TECHNOLOGY READINESS LEVEL OF A SSO-TOKAMAK TRITIUM FUEL CYCLE

Based on the simulation results, candidate technologies for the SSO tokamak fuel cycle were selected and availability levels were defined. Most of the considered technologies are at the development stage TRL 4-6.

FC TECHNOLOGY READINESS LEVEL

To test the technologies in conditions close to those of real operation, integrate technologies, and justify reliability and safety, it is necessary to create large-scale experimental stands and/or small-scale fusion facilities to work with tritium.

- Such a **roadmap** of tritium FC technologies was developed;
- A **draft design** of laboratory stands for FC main technological processes testing was developed;
- **Technical specifications** were prepared for the design of a complex of laboratory stands for working with non-radioactive hydrogen isotopes and tritium trace amounts,
- as well as for a integrated (closed) FC mockup with the main technological processes and systems and research with significant tritium inventory (relevant gas mixtures);
- A **tritium complex design** was prepared for conducting comprehensive research within the framework of national programs on fusion science and nuclear technology.

This infrastructure could allow for research using tritium and ensure timely scientific and technical personnel training, as well as increasing the technological readiness level.

Implementing FC on tokamak without completing preliminary stages carries significant risks