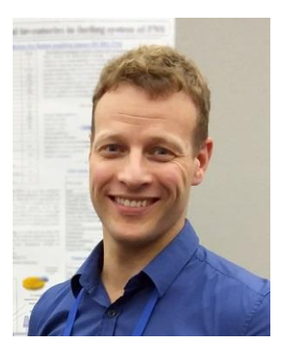

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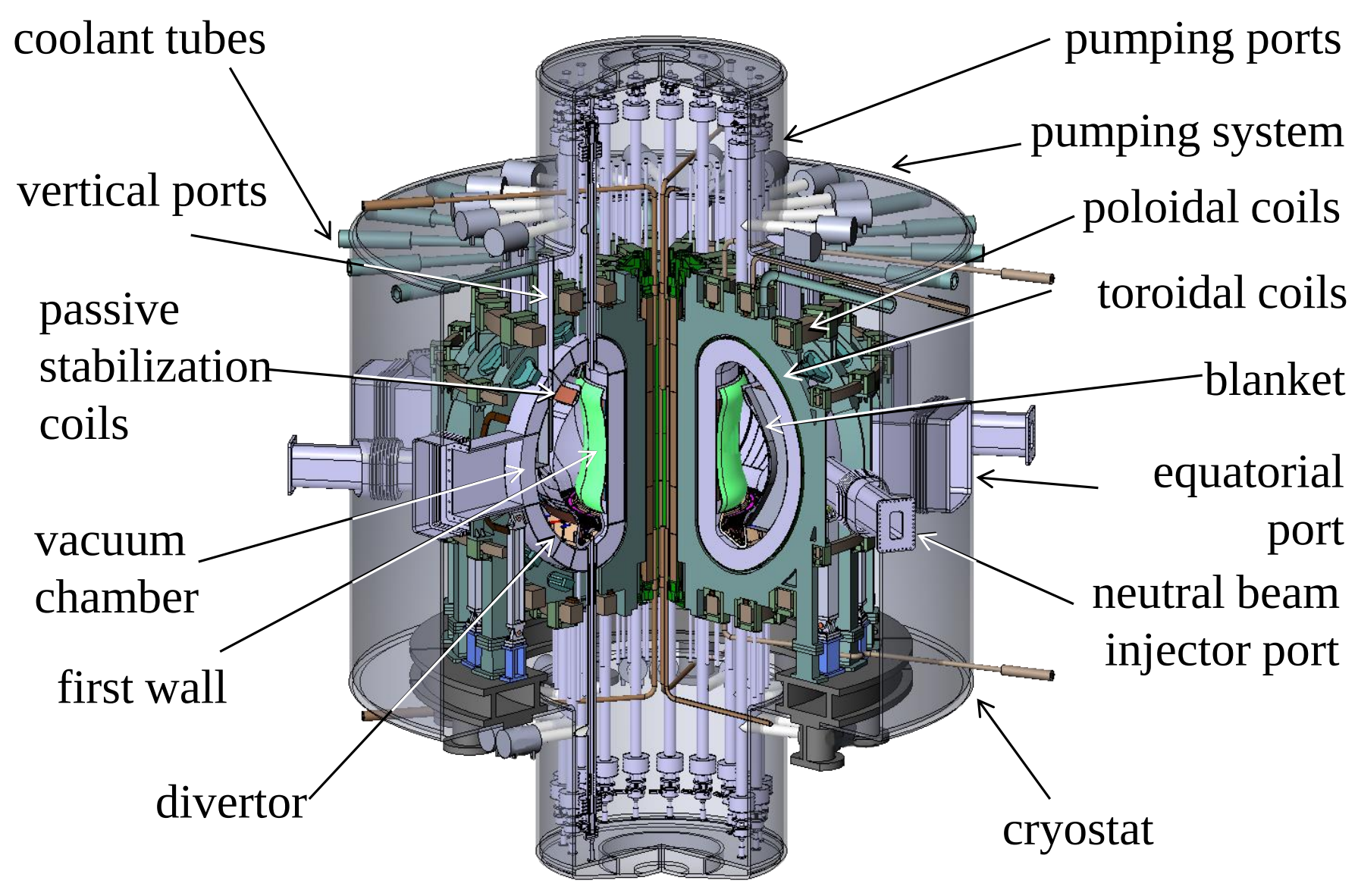
Concept development and candidate technologies selection for the main DEMO-FNS fuel cycle systems

Introduction

Design of a tokamak-based fusion neutron source (DEMO-FNS) with parameters R/a = 3.2m/1m, B = 5T, I_{pl} = 4-5 MA, P_{NBI} = 30 MWт and P_{ECR} = 6MW and power of DT synthesis P_f = 40 MW involves the use of fuel cycle (FC) technologies previously developed as part of the ITER project, as well as those used in JET and TFTR and other tritium systems. The FC architecture and candidate technologies for the main FC systems selected as a result of optimization were compared with existing (TFTR, JET) and design (ITER, CFETR and DEMO) solutions of fusion reactor fuel cycle systems.

The fuel cycle model/computer code FC-FNS (Fuel Cycle for Fusion Neutron Source), which describes the processes in the DEMO-FNS fuel cycle, has been significantly upgraded in the last 2 years. For the first time, a comprehensive simulation of fuel flows in fuel cycle systems was performed for DEMO-FNS, depending on the main and divertor plasma parameters upon injection of an impurity (seeding gas) in divertors. For the basic scenarios of using D^0+T^0- and D^0-beams of additional heating with an energy of Eb = 500 keV with up to 34 MW power, the tritium inventory in the fuel cycle was estimated taking into account its bridging and burning out at different ratios T and D (f_T = T/D) in plasma. It was shown that it is advisable to maintain the tritium fraction in the plasma f_T = 0.5 for the D + T beam, and f_T = 0.6–0.7 for the D beam. Based on the joint modeling of the main and divertor plasma, as well as fuel processing and injection systems, the fuel injection fractions by various systems were optimized.

DEMO-FNS hybrid (fusion-fission) facility



Parameter for DEMO-FNS facility	
Fusion power P_{fus}, MW	40
NBI power P_{NB}, MW	30
Q	∽ 1
T fraction in plasma f_T	0.5-0.7
Plasma density $<n>$, m^{-3}	$6.0\text{-}10 \cdot 10^{19}$
Ne fraction in plasma (at the separatrix) f_{Ne}	0.02
Vacuum chamber volume/FW, m^3/m^2	270/130
Neutron yield G_n, 10^{19} s^{-1}	1.34-1.47
Neutron loading Γn, MW/m^2 / lifetime neutron fluence, MWa/m^2	0,2 / ~2
Tritium breeding ratio (TBR)	> 1.2
Impulse duration, h	> 1000

The main feature of DEMO-FNS is the combination of a relatively small fusion facility (tokamak) with an active nuclear zone based on fissile materials, this allows to:

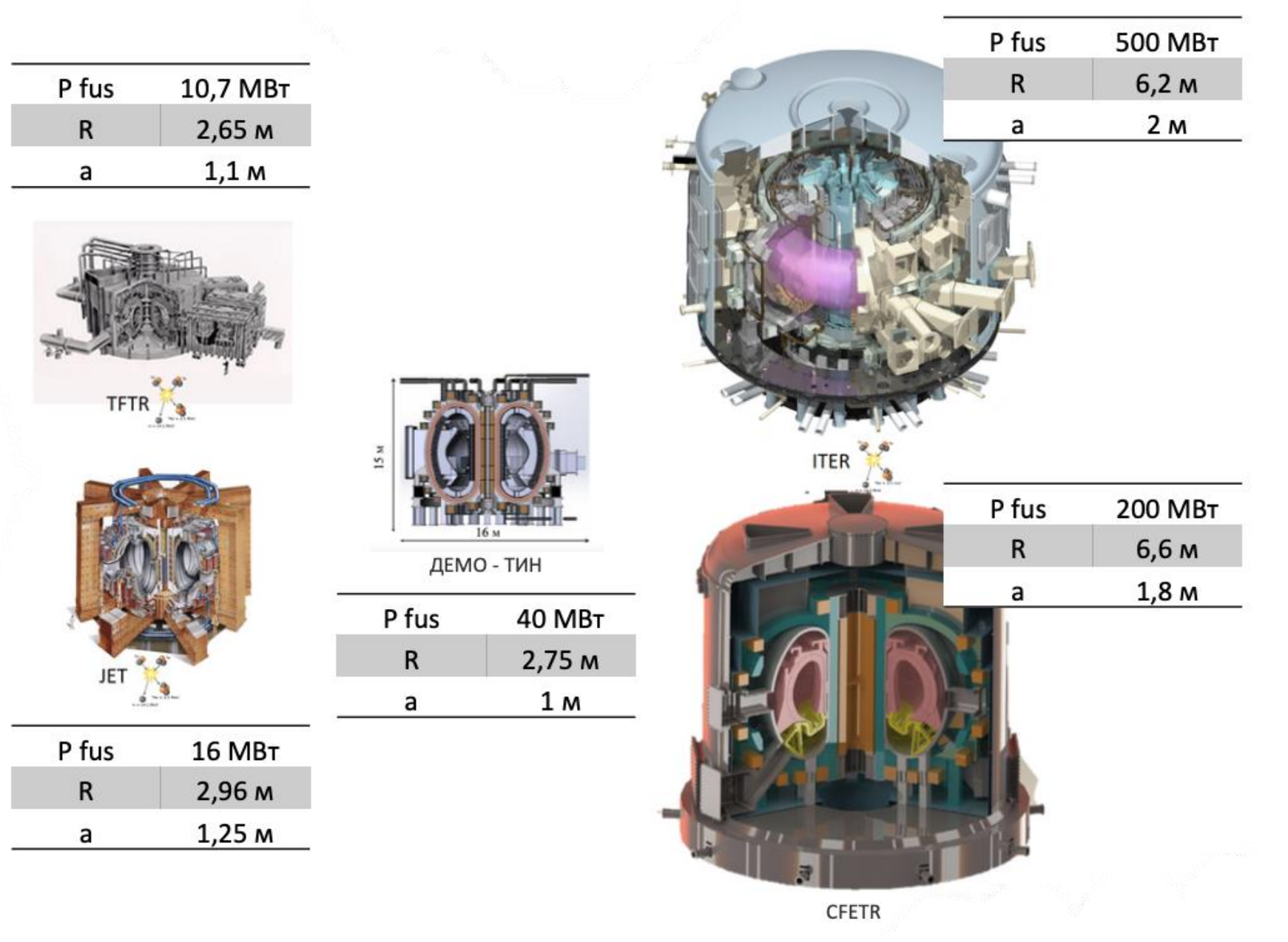
- use available fusion technologies for burning plasma with a pulse time of more than 1000 h, while reaching Q∽1
- obtain significant neutron yield in the active nuclear zone, while using well-known nuclear technologies
- obtain tritium reproduction rate of ∽ 1.2, which is sufficient to meet the fusion facility needs
- provide positive energy output from facility (electric power generation about 200 MW)

DEMO-FNS fuel plant comparison

The closed tritium-deuterium fuel cycle has been implemented at two fusion facilities TFTR (USA) and JET (UK) in the 90th. A ITER (EU), DEMO (EU) and CFETR (China) facilities fuel cycles are designed and full-scale testing of they individual parts are also underway. These two groups of plants differ greatly both in they own scale and in the tritium amount in the fuel cycle. DEMO-FNS by its characteristics occupies an intermediate position between these two groups. Therefore, in the DEMO-FNS fuel cycle, it is possible to use both proven small-scale technologies and adapt technologies developed for larger facilities.

Fusion facility	T inventory in plant, g	T flow to vac. vessel	T breeding ratio (TBR)
TFTR	up to 25	90 g /all time	-
JET DTE1	20	100 g /all time	-
JET DTE2	60	up to 13,5 g/day	-
DEMO-FNS	**up to 2 000**	**~ 200 g/hour**	**more 1,2**
ITER	up to 4 000	~ 0,3 - 1 kg/hour	test blanket
CFETR	up to 4 000	~ 300 g/hour	less 1,1
DEMO	up to 10 000	~ 1kg/hour	~ 1,1

The parameter “Tritium flow to vacuum vessel” is a function of the plant fusion power. The parameter “Tritium inventory in plant” mainly depends on the technologies applied in FC.

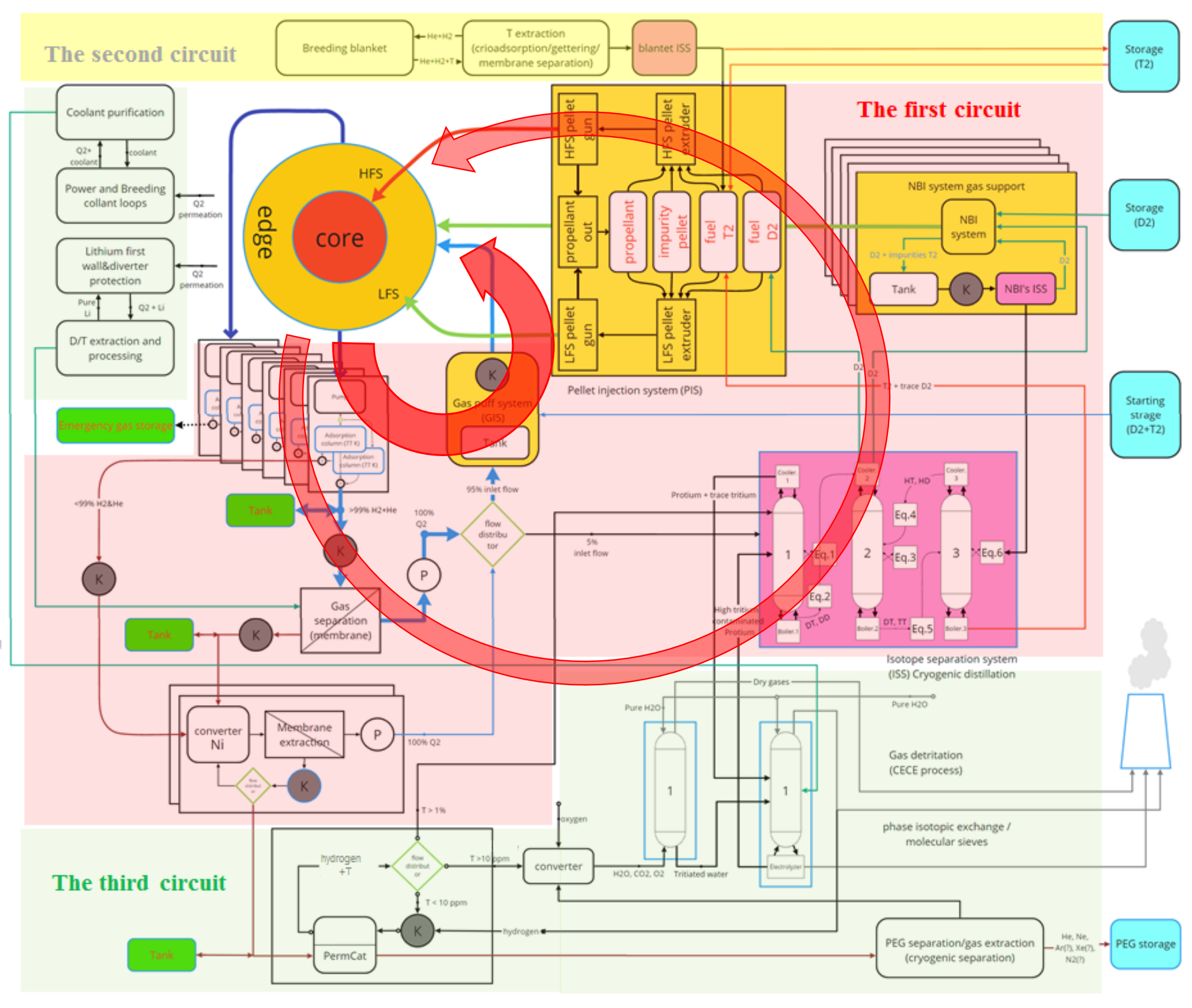


DEMO-FNS fuel cycle main characteristics:

- a relatively small amount of fuel (tritium and deuterium) is required to create and maintain a plasma discharge ensuring Q~1;
- fuel cycle systems should support a steady state mode of processing and fuel mixture supplying, since the steady state plasma mode is assumed;
- monoisotopic flows is required for injection in some scenarios (pure deuterium in a neutral injection system or pure tritium for a pellet injection system);
- minimum tritium (and other hydrogen isotopes) inventories must be ensured.

Promising Technologies of DEMO-FNS Fuel Cycle

Promising technologies for fuel cycle systems were selected.
As a result of optimization, it was assumed that 3 circuits will be allocated in the fuel cycle: (i) for the fast processing of tokamak “exhaust” gases, (ii) for the separation of tritium from the reactor blanket and (iii) for the processing of tritium-containing wastes, trapping of tritium from process streams (in including from the air of working rooms in emergency situations) and the process gases separation.

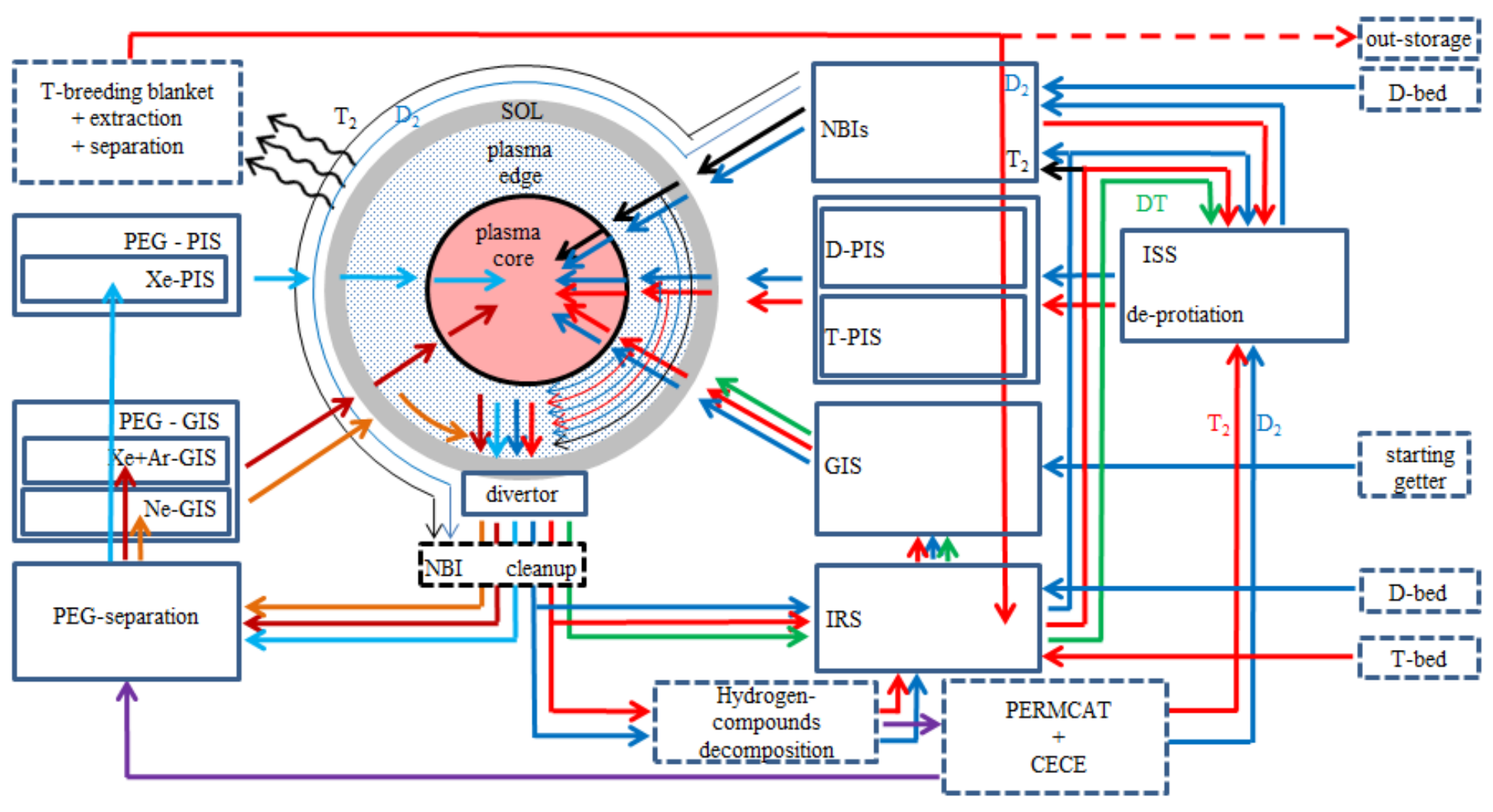


The main systems of the DEMO-FNS facility fuel cycle.
The three main contours of the fuel cycle are highlighted in different colors.

Fuel cycle function	Applied methods
providing fuel to injection systems into the plasm	gas, pellet & neutral beam injection
removal of gases from the plasma chamber (divertor)	cryopanels & turbomolecular pumping
hydrogen extraction from gas mixtures	metal membranes, cryoadsorption, getters
hydrogen isotopes separation	cryodistillation, preparative gas chromatography
radioactive waste processing (gas and liquid flows detritiation)	CECE-process, phase isotopic exchange, waste conditioning, adsorption, water rectification
PEG extraction	membranes methods, cryoadsorption

Simulation for fusion neutron source DEMO-FNS

The DEMO-FNS Fuel Cycle Concept



FC-FNS code:

«FC-FNS» code (NRC "Kurchatov institute, RF) is intended for modeling hydrogen isotopes flows and inventories in fueling systems, it’s also used as an analytical tool and has been actively developing in both this ways.

The modified FC-FNS code allows the DEMO-FNS main parameters calculation depending on the core and divertor plasma parameters, it can be used for analysis, optimization and FC systems further design.

The core plasma receives particles from three sources, comparable in contribution to the core density. A change in the isotopic composition of the core plasma affects the systems for pumping and processing gases, as well as the fueling systems, which must provide the specified values of f_{core}^T.

Loss of particles from the plasma:

$$\boldsymbol{S_{NB}^{T+D} + S_{pel}^{T+D}} + S_{sep}^{T+D} - S_{fus}^{T+D} = S_{out}^{T+D}$$

fueling — neutral flux from divertor — fusion

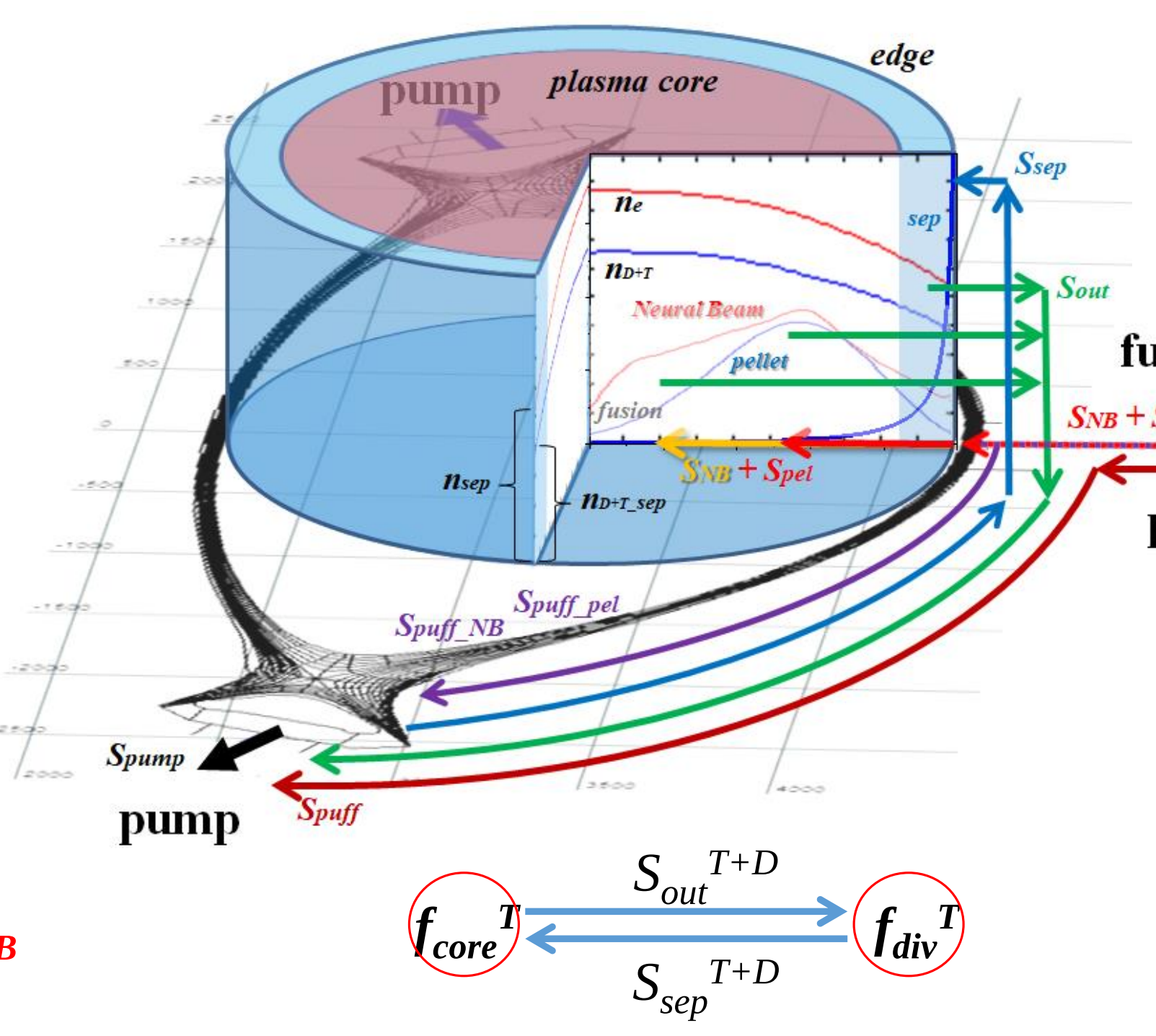
pump $\boldsymbol{p_n c_p} = S_{puff}^{T+D} - S_{sep}^{T+D} + S_{out}^{T+D}$

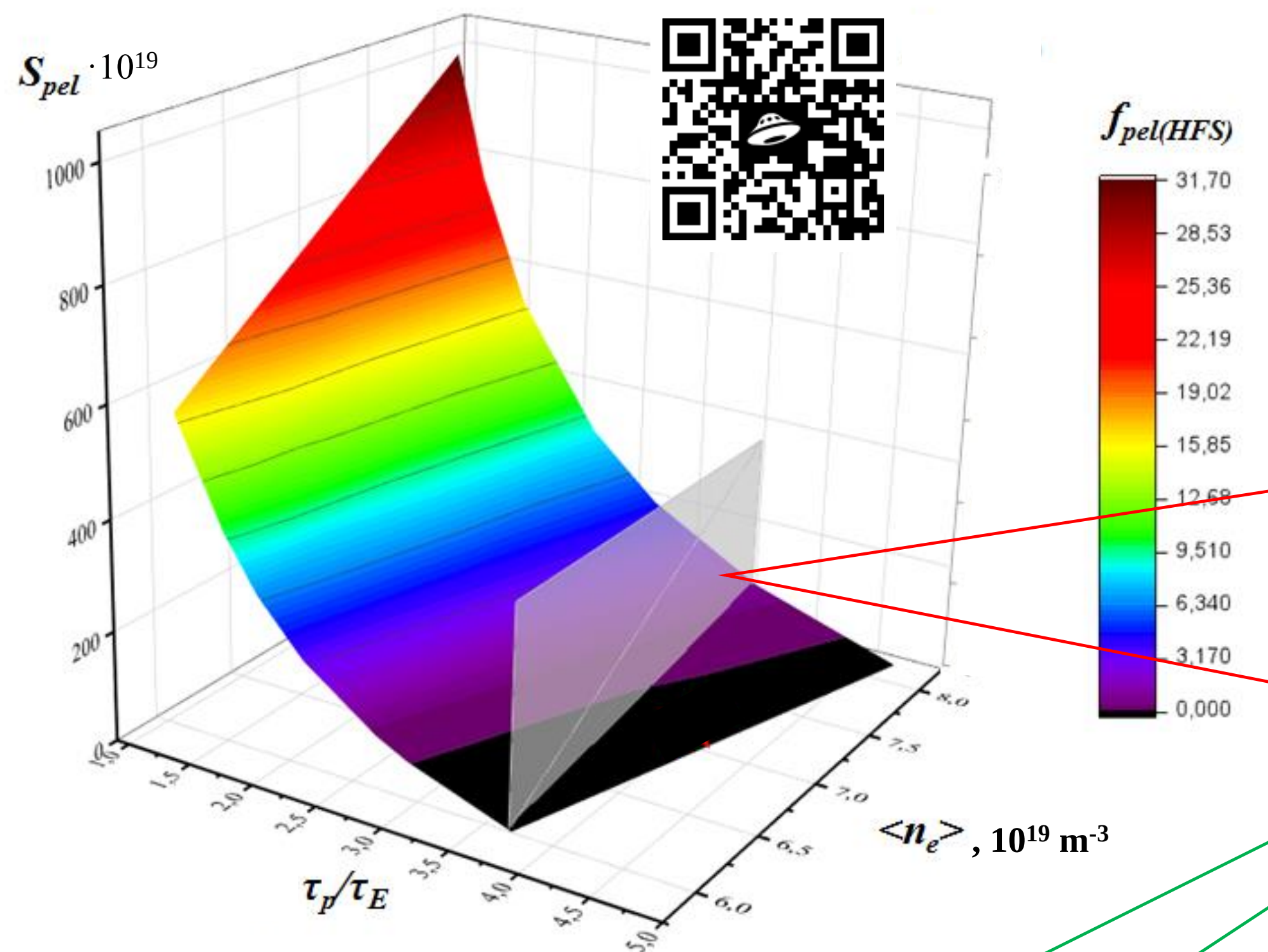
puff $S_{puff}^{T+D} = S_{GIS}^{T+D} + S_{puff(NB/pel)}^{T+D}$

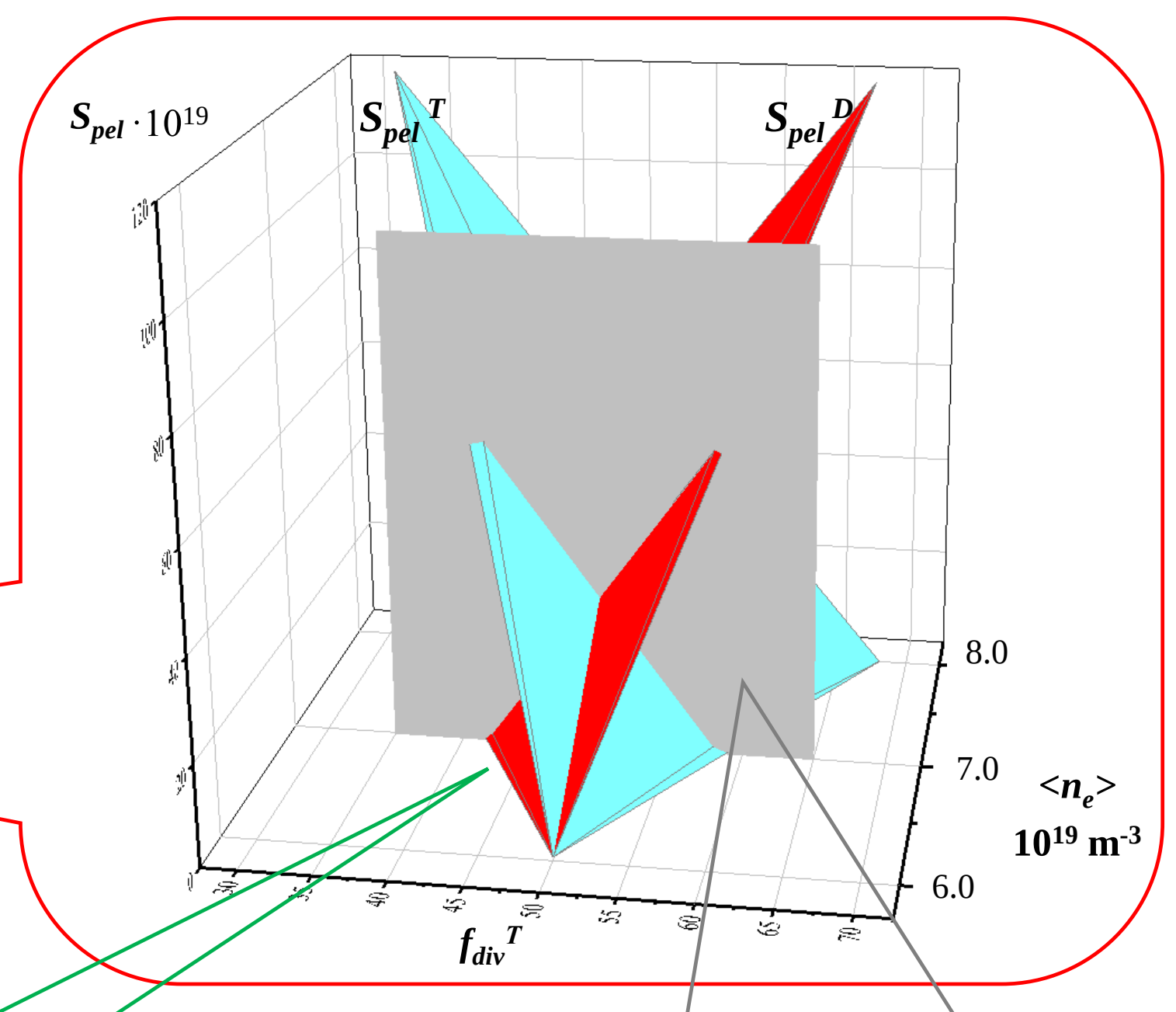
Since the hydrogen isotope source profiles from different particle sources do not match, particles from these sources have different retention times.

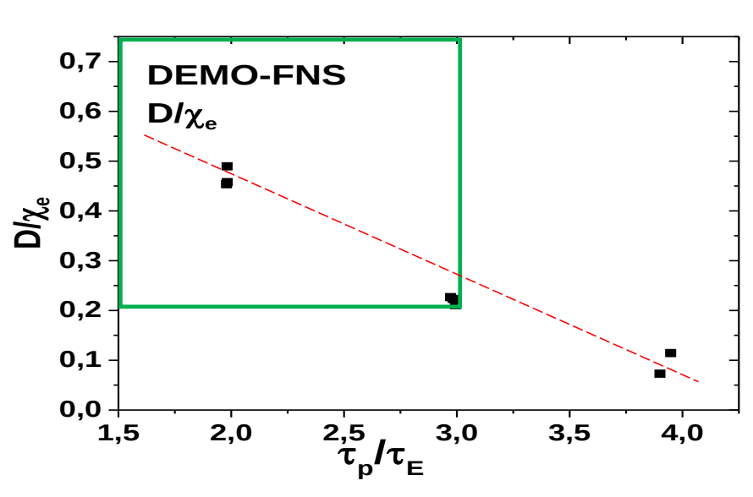
Particle balance in the main plasma

$$N_{core} = N_{sep} + S_{NB} \cdot \tau_{NB} + S_{pel} \cdot \tau_{pel} + S_{sep}\, \tau_{sep} - S_{fus} \cdot \tau_{NB}$$



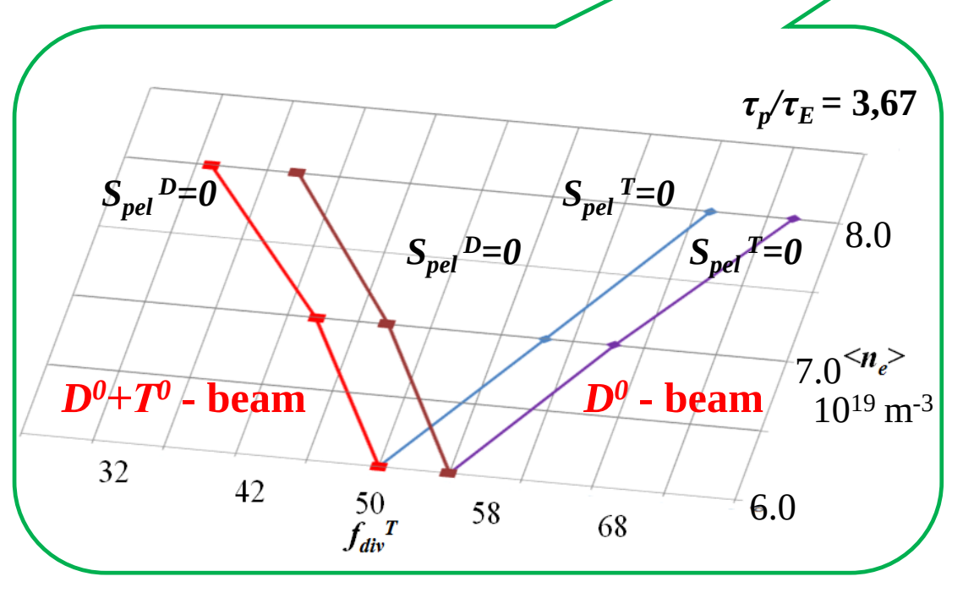




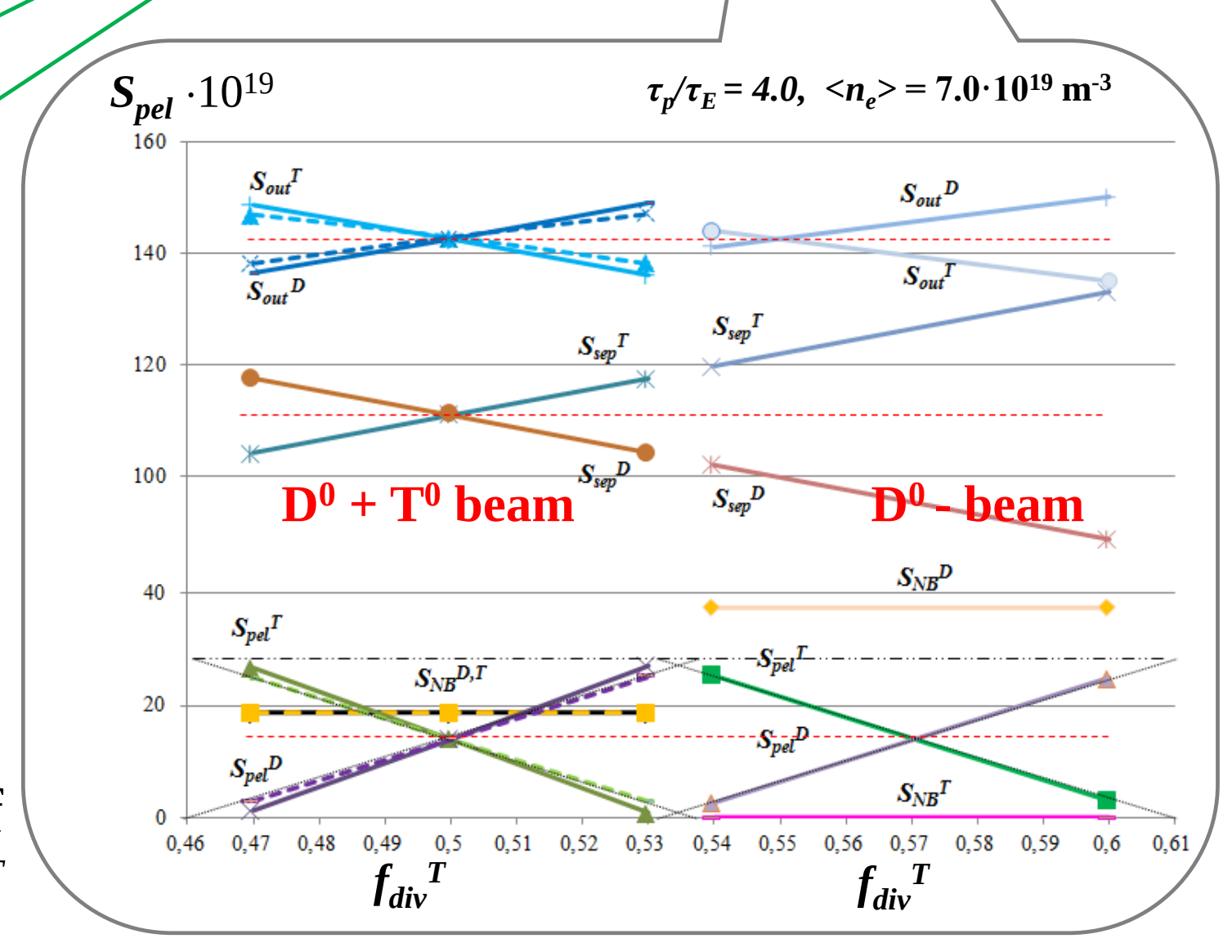


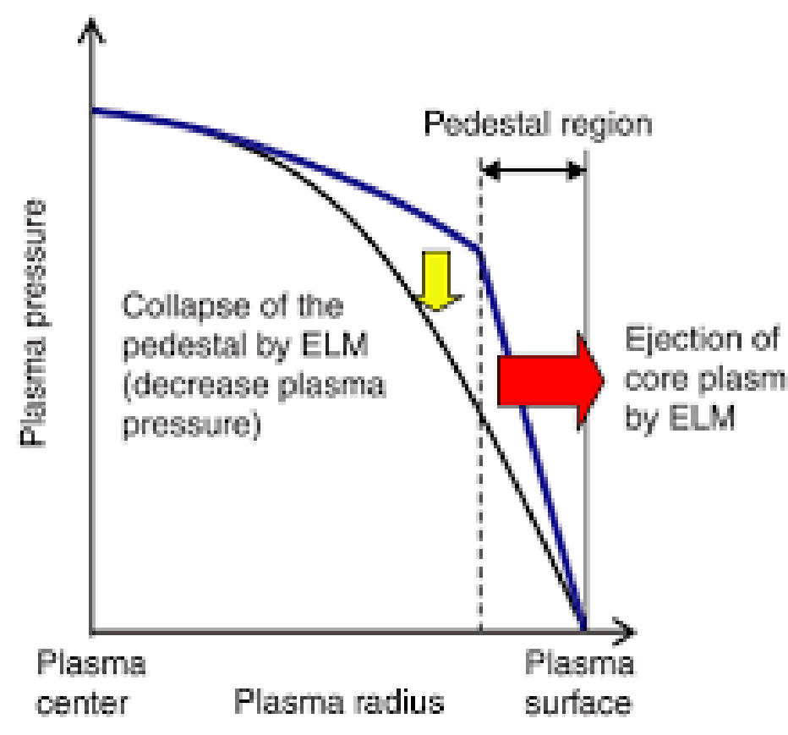
M. Valovic 2005
CTF:
ν* ~ 0.1
D_{eff}/χ_e = 0.4

A. Polevoi 2005
ITER:
ν* = 0.01-0.7
D/χ_e = 0.2-0.75



S_{pel}^T and S_{pel}^D plots intersections of the 0 values and S_{pel}^{T+D} - is the f_{div}^T operation window boundaries





ELMs formation for the basic scenario of DEMO-FNS operation:

The frequency of the ELM formation required to obtain the permissible value δW_{ELM} ~ **0,5 MJ** should be **~ 16 Hz** - that is, pellets the injection frequency f_{pel} by HFS + LFS

In this case, the flux of particles from the plasma caused by ELM S^{DT}_{ELM} = $\alpha_{ELM} P_{SOL}(N_{ped}/W_{ped})$ ~ $\boldsymbol{5 \cdot 10^{21}\ s^{-1} = 9\ Pa\, m^3 s^{-1}}$.

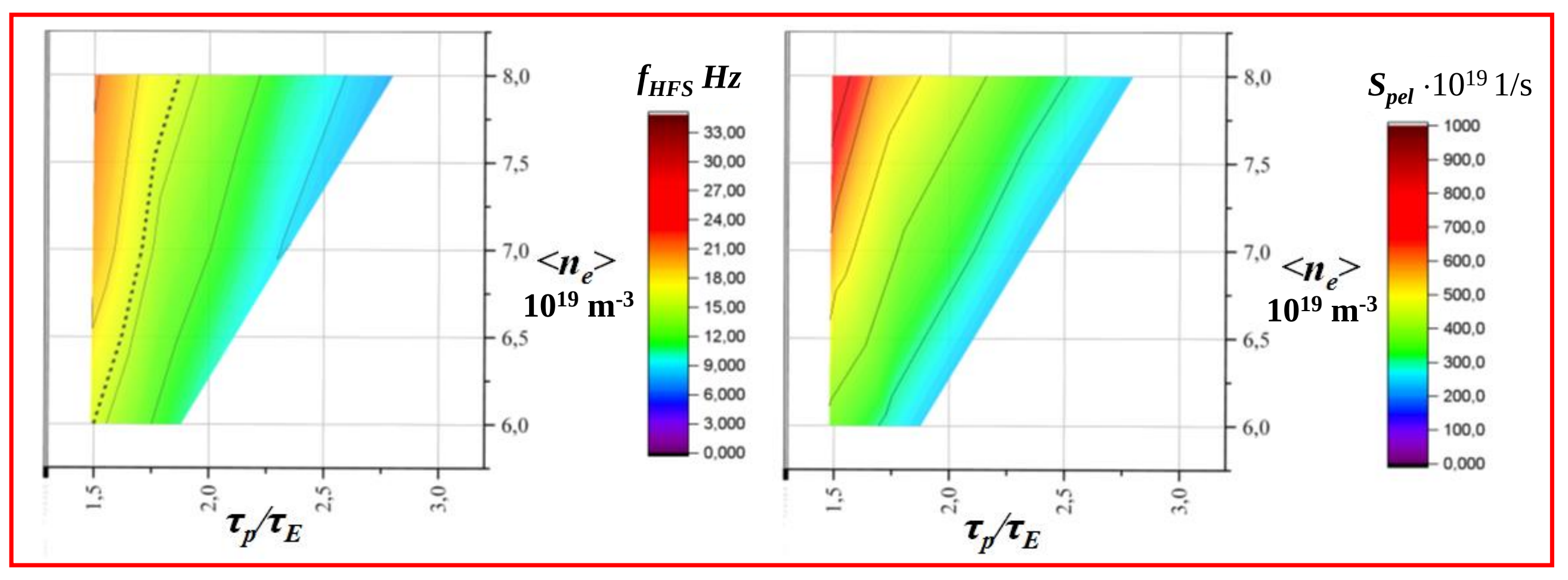
Particle balance in the main plasma

$$N_{core} = N_{sep} + S_{NB} \cdot \tau_{NB} + (S_{core\_pel} + S_{ELM\_pel}) \cdot \tau_{pel} + S_{core\_LFS} \cdot \tau_{sep} + S_{sep} \cdot \tau_{sep} - S_{fus} \cdot \tau_{NB}$$

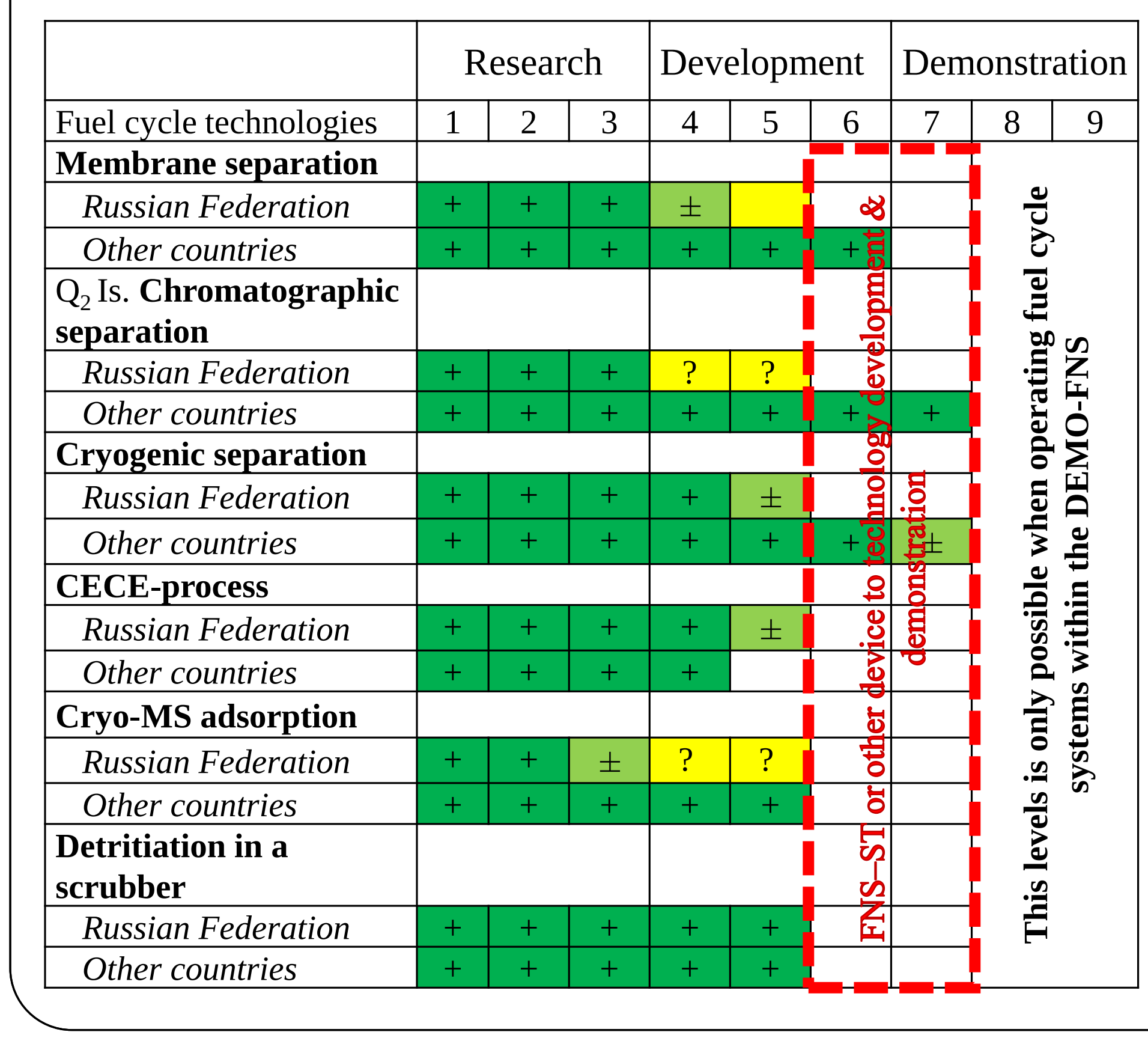
The operation window will be limited by the condition $S_{out} = S_{SOL} + S_{ELM} > S_{ELM}$.

$N_{pel} \leq 2.6\text{-}3.5 \cdot 10^{20}$ particles for n_e = 6.0-8.0·10^{19} m^{-3} (5% of D+T particles in core).

For the considered parameters range it is necessary to apply additional ELMs stimulation.



FC technologies readiness level assessment and T-systems development roadmap



	Research			Development			Demonstration		
Fuel cycle technologies	1	2	3	4	5	6	7	8	9
Membrane separation									
Russian Federation	+	+	+	±					
Other countries	+	+	+	+	+	+			
Q_2 Is. **Chromatographic separation**									
Russian Federation	+	+	+	?	?				
Other countries	+	+	+	+	+	+	+		
Cryogenic separation									
Russian Federation	+	+	+	+	±				
Other countries	+	+	+	+	+	+	±		
CECE-process									
Russian Federation	+	+	+	+	±				
Other countries	+	+	+	+					
Cryo-MS adsorption									
Russian Federation	+	+	±	?	?				
Other countries	+	+	+	+	+				
Detritiation in a scrubber									
Russian Federation	+	+	+	+	+				
Other countries	+	+	+	+	+				

FNS–ST or other device to technology development & demonstration

This levels is only possible when operating fuel cycle systems within the DEMO-FNS

The maturity assessment of the tritium and deuterium handling technologies existing in RF for use in the DEMO-FNS fuel cycle was made. For the analysis, the Technology Readiness Level (TRL) method was applied.

TRL level of enabling technologies compiling the fuel cycle of DEMO-FNS was evaluated as TRL 4-5 level and can be brought up to TRL 5-6 in a short time.

When forming the Roadmap, the main priorities for the technology development should be considered the current levels, as well as possible alternatives. An important part of the Roadmap should be the technologies integration and they development consistently at stands and different-scale installations (for example, FNS-ST).