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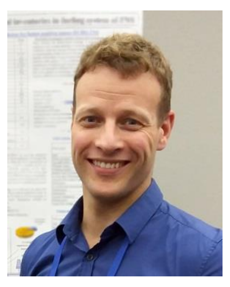


1th OSSFE conference (Open Source Software for Fusion Energy)

18 March 2025 (online)

NATIONAL RESEARCH CENTRE "KURCHATOV INSTITUTE"

SYSTEM MODELING AND OPTIMIZATION OF TOKAMAK TRITIUM FUEL CYCLE

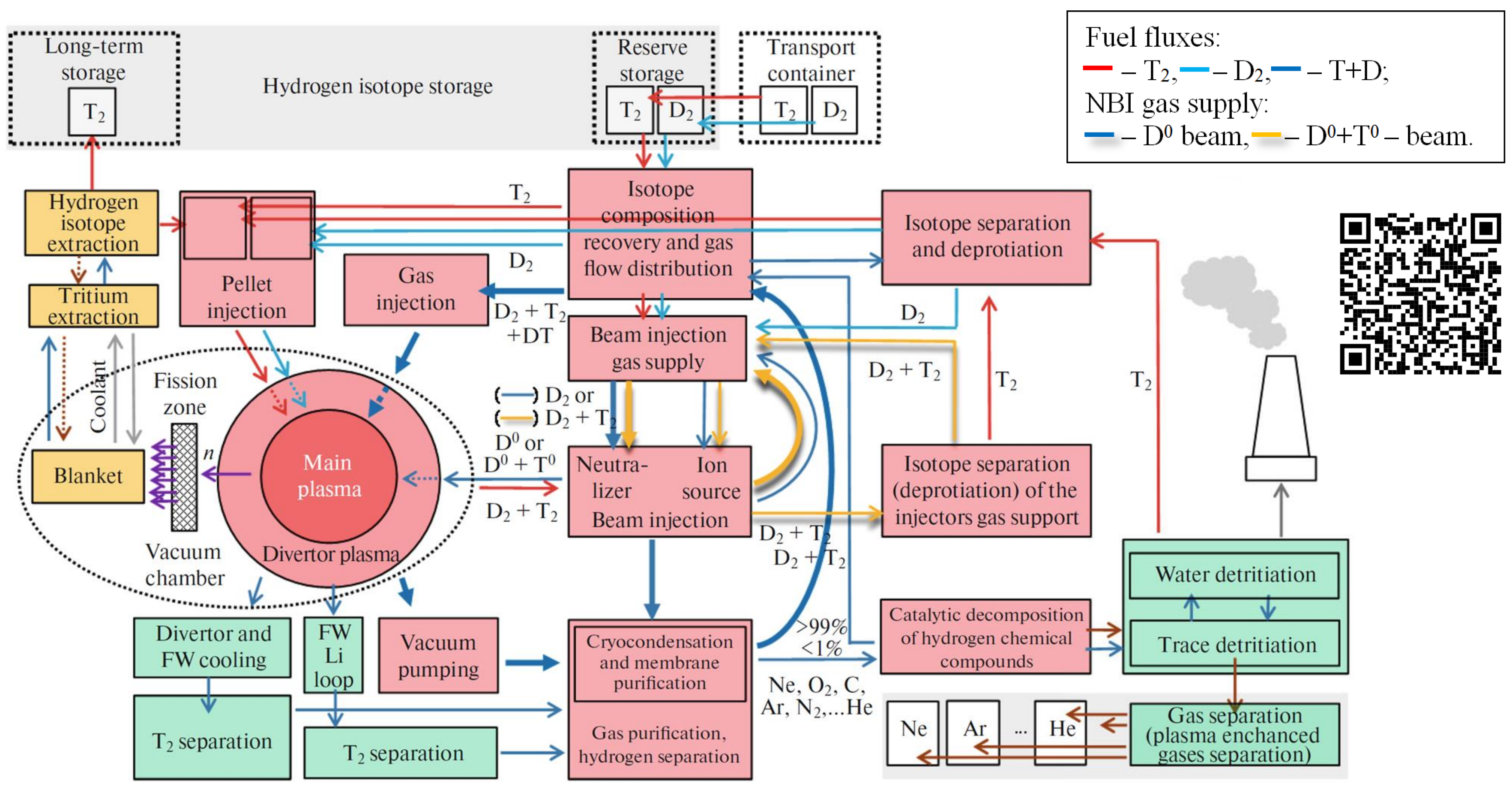
INTRODUCTION

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). The standard models used [*M.A. ABDOU et. al., Fusion Technology, 1986* et al] cannot take into account most of the processes occurring in the vacuum chamber and the features of the technological processes in the fuel cycle systems of the plant.

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). Analysis of the FC operation is performed on the basis of advanced SOLPS, ASTRA, and FC-FNS codes combination taking into accounting for interaction of gas flows with plasma. Effects of specific gas mixture flows on plasma optimization and minimizing the tritium inventory at the site are treated in details.

BACKGROUND and CHALLENGES

Commercial codes for simulation (Aspen, Ecosim et al) the behavior of hydrogen isotopes in technological systems require information about the engineering parameters of the systems and the selected technologies - for fuel cycle optimization such information is missing and must be found. System codes use very rough models or have a large number of free parameters. A tool is needed to R&D a steady-state tokamak fuel cycle, optimize it and match it with the processes in the vacuum chamber and plasma, with the technologies of the systems and reduce the amount of hydrogen (tritium) in the facility.



Block diagram of fuel cycle systems. Main circuits are divided by colors: ■ – fast processing of the exhaust, ■ – tritium extraction from the blanket, ■ – processing of tritium-containing waste.

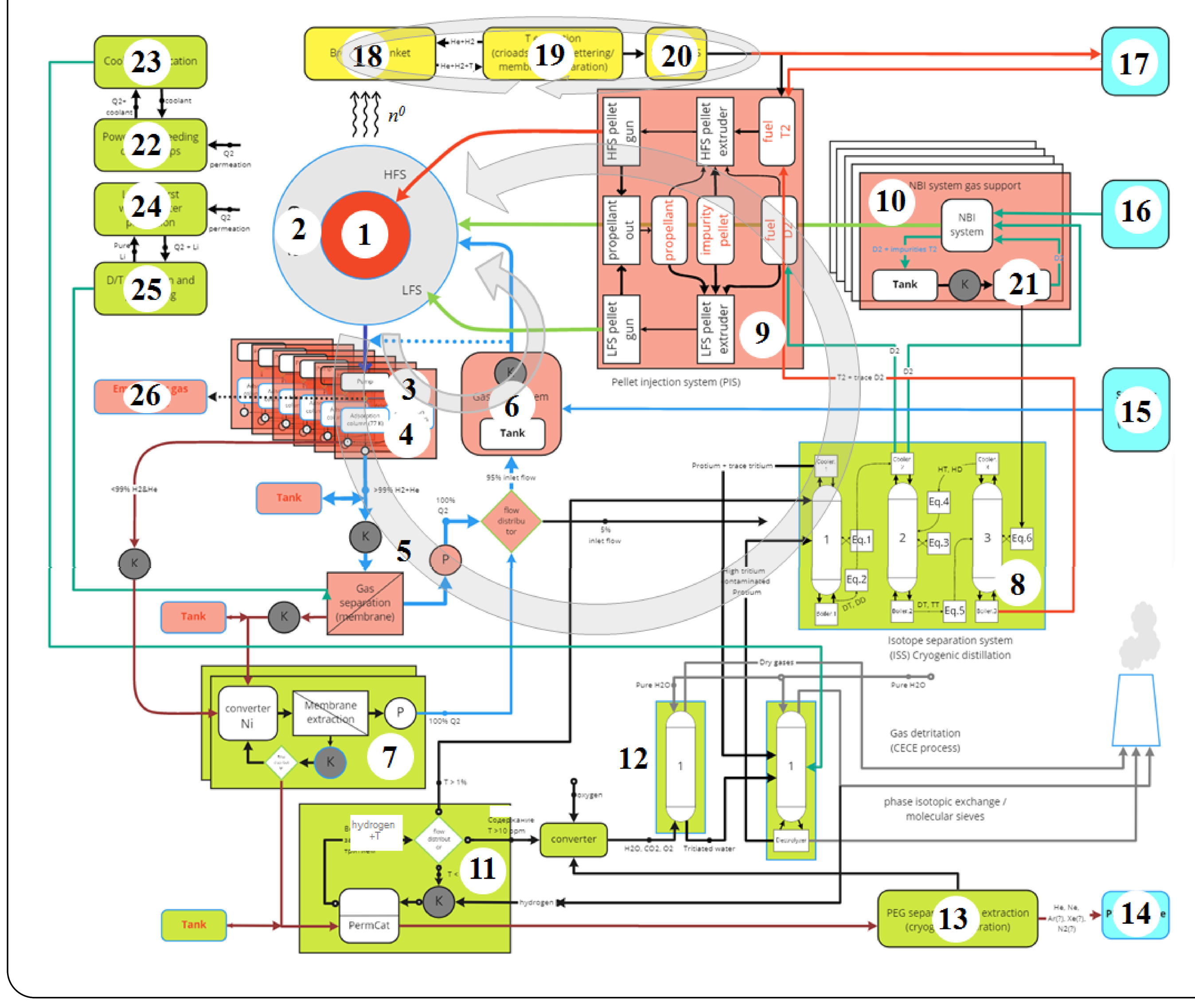
Using the **MS Excel** software package, a model of a steady-state fuel cycle for a controlled fusion plant tokamak based with plasma fueling, additional power injection and steady-state processing of the gas mixture was developed in 2013.

The behavior of hydrogen isotopes is modeled by solving zero-dimensional equations for each element of the model.

The amount of hydrogen up to 2014 - through the "residence time", then taking into account macro parameters - temperature, pressure, volume, flows.

v 1.0	2013	**Electronic model: calculation of T-flows, assessment of T inventory**
v 2.0	2014	Model development: T-inventory, D:T=1:0.05 NBI scenario
v 4.3	2014	T-breeding in a blanket, + calculations by analytical model [Abdou]
v 5.0	2015	New fuel cycle design, increasing the number of systems
v 5.1	2015	Changing the architecture of the fuel cycle , calculation for T, D and H
v 5.3	2016	Dynamics of hydrogen content in fuel, T-dynamics in NBI
v 5.6	2016	Changes in the approach to fuel injection
v 5.7	2017	Arbitrary D:T ratio in plasma
v 5.8.8	2017	D:T = 1:0 for NBI, arbitrary fuel flows through VV
v 6.0	2018	Separate injection of D_2, T_2 - pellets, gas separation
v 7.0	2018	D/T/H isotopic composition in the fuel cycle - by the iteration method
v 8.0	2019	Taking into account the influence of the neutral flow from the divertor
v 9.0	2019	**Integrated modelling – integrating algorithms into code**
v 10.0	2019	Splitting one working file/module into separate ones
v 11.0	2020	**New plasma model, diffusion times for sources**
v 12.0	2020	Calculations of all NBI gas supply scenarios - in parallel
v 13.0	2020	D/T ratio in the divertor, the effect on the core plasma composition
v 14.0	2020	Automated calculation of pellet injection frequencies
v 14.2	2021	Effect by ELMs particle loses from plasma – first release
v 15.1	2021	Adaptation for FNS-ST, change of diffusion parameters
v 15.2	2021	T-beam modeling for FNS-ST
v 15.8	2021	**Precision accounting of the influence of ELM, pacing on LFS**
v 16.0	2022	**Upgraded D/T isotopes inventory algorithm in ISS**
v 16.1	2022	Optimization of the gas support for neutral injection system
v 16.2	2022	**Modernization for using times τ_i from ASTRA**
v 16.3	2022	Using partial times from ASTRA for FNS-ST

The key difference from similar models is the <u>separate simulation</u> 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.



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

Fuel Cycle (with technologies) for Fusion Neutron Source (RF) projects

METHODS and MODEL

An approach to simulations of tritium fuel cycle (**FC**) systems and calculation of the amount of tritium at the facility, consistently with the core and divertor plasma was developed . In this approach, similarly to [*H.D. PACHER et al, J. Nucl. Mater. 2015*], the state of the core (inside the separatrix) and edge (outside the separatrix) plasma is simulated by a ASTRA and SOLPS4.3 combination, **the particle flows in the fuel cycle systems are simulated by the <u>FC-FNS code</u>.**

SOL simulation (SOLPS) → **Core plasma simulation (ASTRA+NUBEAM)** → **Fuel flows (FC) simulation (FC-FNS)** → **FC Tritium inventory calculation**

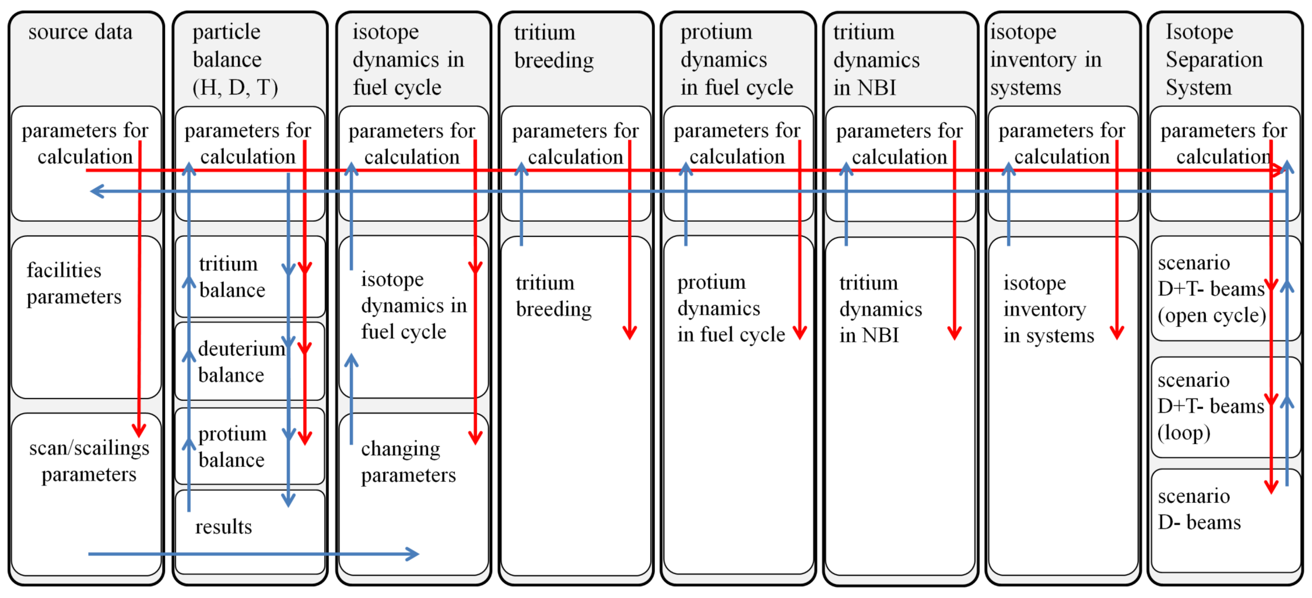
Technology selection **FC design optimization**

The integration between these three independent codes is carried out by an indirect scheme, where the output data from one code is parameterized and further used as input data in the other code.

This allowed us to create an efficient calculation workflow that describes the interaction of various components of the model with very different calculation times.

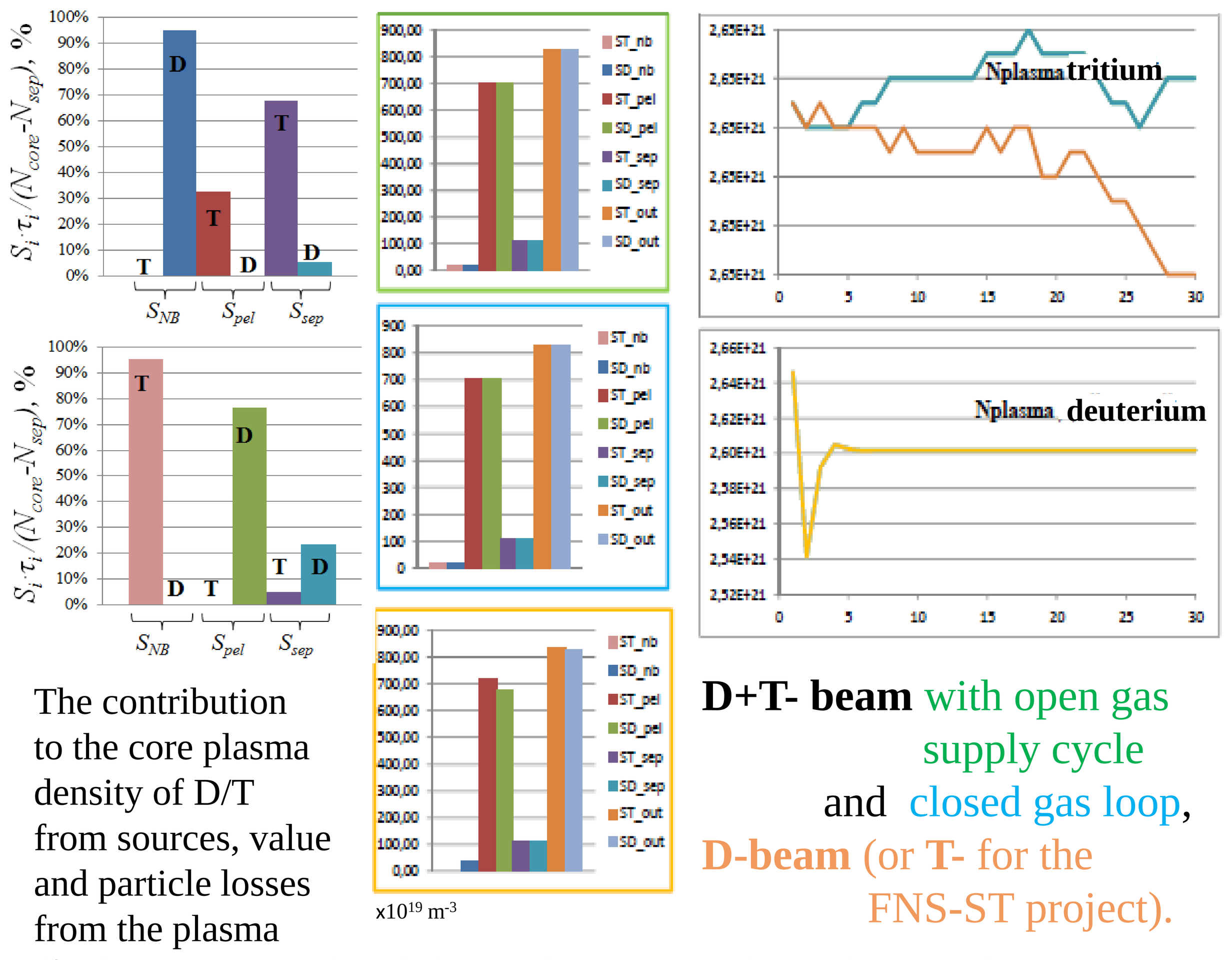
FC-FNS (Fuel Cycle for Fusion Neutron Source) code

FC-FNS code is divided into separate working modules that interact with each other via cross-references written as equations for cells (**MS Excel tables**). All calculations in the code modules are organized to avoid the appearance of "cyclic references".



The calculation parameters are specified in the "Initial data" file. The file contains several "worksheets" - the first one contains a table with the calculation parameters, and most of the results are output there. This allows the user to perform calculations using only one file as an "interface". The remaining files and their "sheets" contain intermediate results adapted for debugging or assessing the correctness of the calculations.

The input parameters are the geometric and physical parameters of the tokamak with subsystems: geometric dimensions of the vacuum chamber, particle diffusion times, plasma density, fusion power, injection system parameters, vacuum chamber pumping modes, injectors, tritium breeding system shutdown period, etc. **The main parameters are the deuterium/tritium fraction in the plasma and the permissible fraction of protium in the fuel mixture.**



The contribution to the core plasma density of D/T from sources, value and particle losses from the plasma (for beam scenarios) and change the D/T particles in the core plasma.

When injection parameters is not optimal ones, a deviation of the plasma density and the tritium fraction (f_{core}^{T}) in it occurs - this mode <u>can also be stationary</u>.

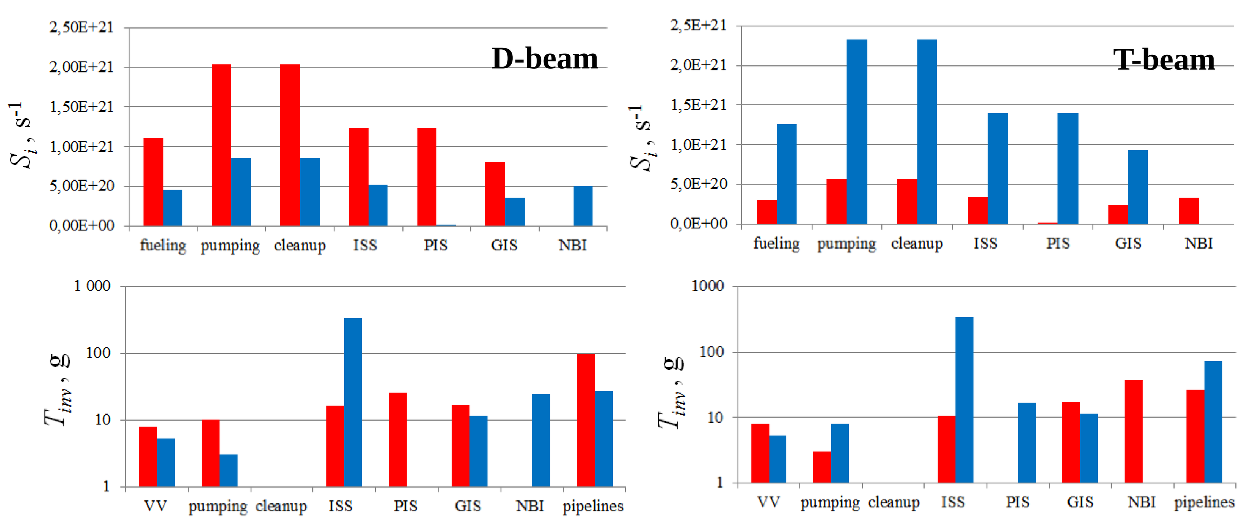
To simulate the processes of establishing a balance of flows in the plasma core and fuel cycle systems, an iterative solution of the balance equations in the plasma and fuel cycle is carried out.

D+T- beam with open gas supply cycle and closed gas loop, D-beam (or T- for the FNS-ST project).

At the first step, the plasma density, tritium fraction in the main plasma, divertor and pedestal are specified, **at all subsequent steps, their values are calculated based on the values of the fuel component flows D and T.**

When the plasma density changes, other parameters will change (P_{fus}, P_{SOL}, τ_E, τ_p et al), **which are not explicitly calculated in the FC-FNS code** – their evolution is taken into account using scalings by SOLPS+ASTRA based on integrated modelling.

FNS-ST project



Particle flows T - ■ and D - ■ through FC systems and the tritium inventory

The model/code allows to describe the behavior of all hydrogen isotopes <u>in the steady-state mode</u> in fuel cycle systems (with new geometry with gas "real time" processing without accumulating in operational storage). Processes (isotopes transport) in all fuel cycle systems/ elements can be simulated. The isotopes inventory is estimated by precision models.

For plasma parameters and expected transport characteristics/losses, it is possible to estimate the **separate isotopes flow values of required to control the plasma composition and density.** Fuel component flows in the fueling, injection systems and isotopes inventory in fuel cycle are calculated/simulated taking into account used technologies and characteristic processes in them.