KURCHATOV INSTITUTE
NATIONAL RESEARCH CENTRE

THE CONCEPT OF TRITIUM FUEL CYCLE FOR A TOKAMAK-BASED FUSION NEUTRON SOURCES IN THE RF

S.S. ANANYEV [a], *Ananyev_SS@nrcki.ru*
B.V. IVANOV [a], A.S. KUKUSHKIN [a,b],
M.R. NURGALIEV [a], B.V. KUTEEV [a,b]

[a] NRC “Kurchatov Institute”, Moscow, RF
[b] NRNU MEPhI , Moscow, RF

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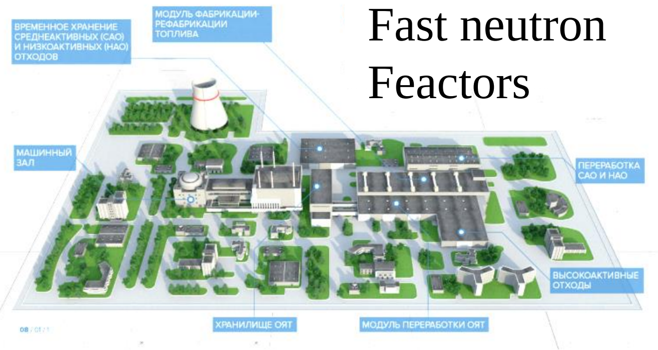
Power system structure with Fission and Fusion Reactors

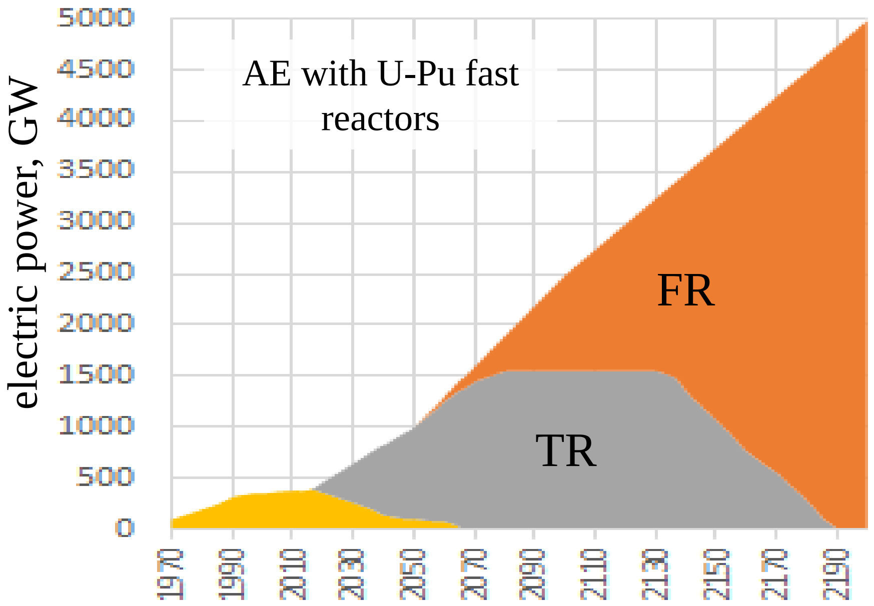
U-Pu cycle

A new (target) nuclide is produced in the same active zone (fuel rod) as the original one...

All fuel needs to be reprocessed!



Fast neutron Feactors



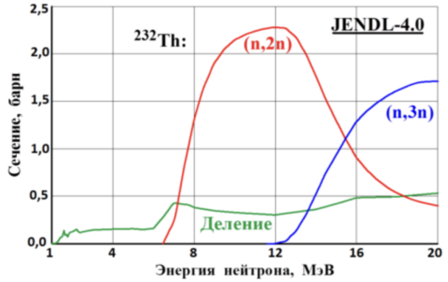
Fast reactors will not produce fuel for thermal reactors - they will displace them!

U-Th cycle

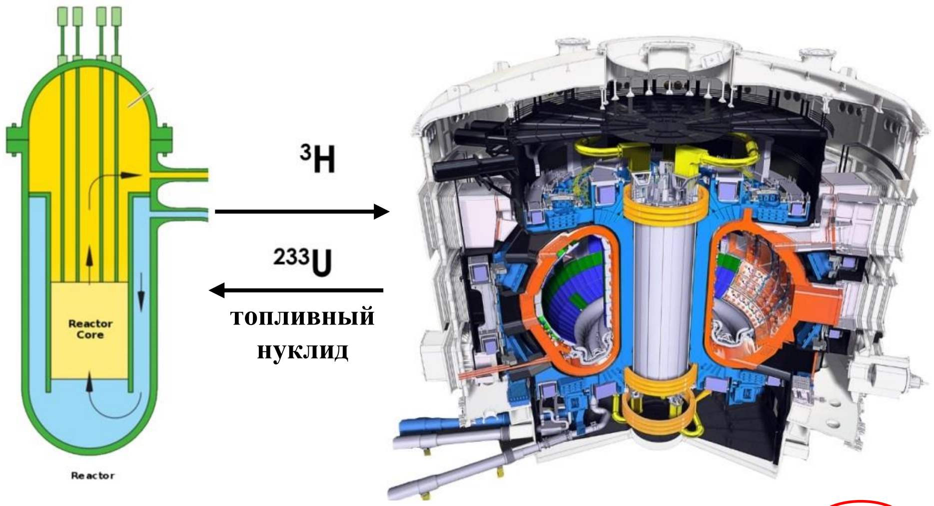
Thermal neutron Reactors + Hybrid Reactor (Fusion)

$${}_3\mathrm{Li}^6 + {}_0\mathrm{n}^1(\text{thermal}) \rightarrow {}_2\mathrm{He}^4 + {}_1\mathrm{T}^3 + 4.78\ \mathrm{MeV}$$

$${}_3\mathrm{Li}^7 + {}_0\mathrm{n}^1(\text{fast}) \rightarrow {}_2\mathrm{He}^4 + {}_0\mathrm{n}^1 + {}_1\mathrm{T}^3 - 2.47\ \mathrm{MeV}$$



Cross sections for reactions depending on the incident neutron energy for ^{232}Th (according to the JENDL-4.0 library)

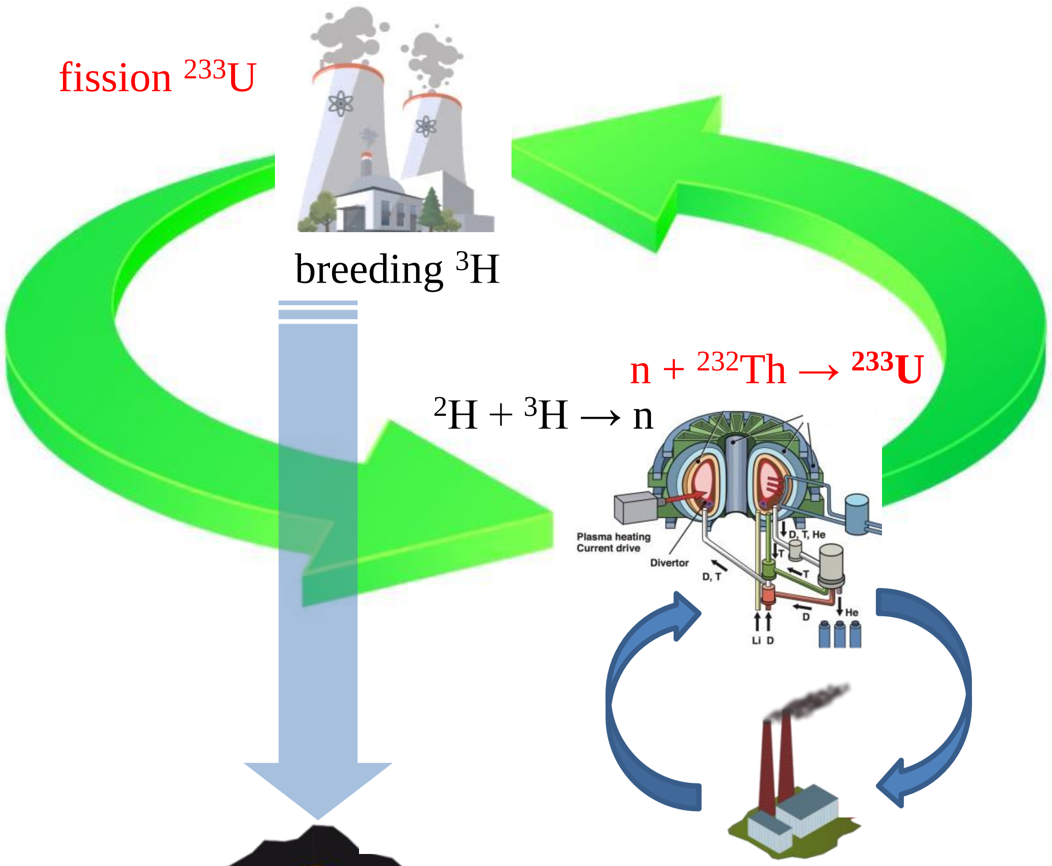


$${}_1\mathrm{D}^2 + {}_1\mathrm{T}^3 \rightarrow {}_2\mathrm{He}^4 + {}_0\mathrm{n}^1 + 17.58\ \mathrm{MeV} \longrightarrow \mathrm{n} + {}^{232}\mathrm{Th} \rightarrow {}^{233}\mathrm{U}$$

In this approach:

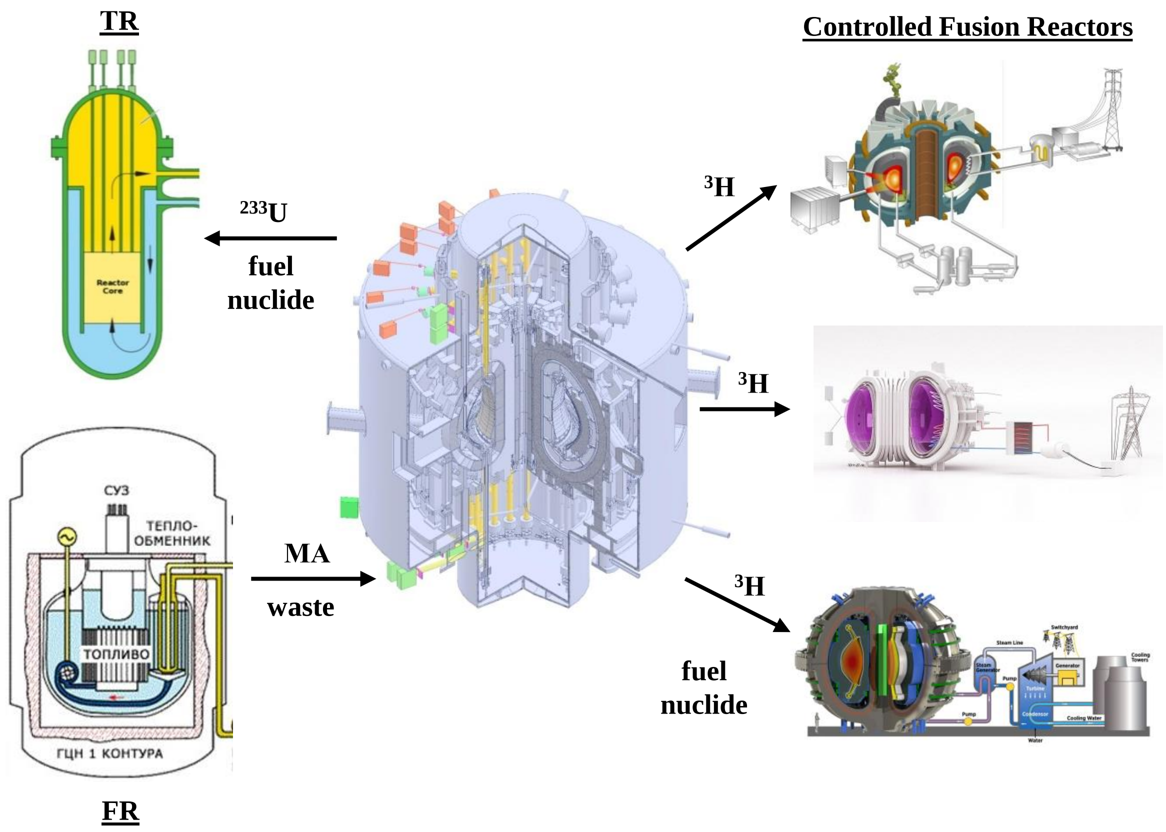
Fusion (hybrid) reactor (neutron source) produces neutrons... with the use of which a nuclide is produced... which is burned in TR... that generate electricity... which should provide HFR and other consumers (humanity)!

Prospects for an energy system with Fission and Fusion Reactors



Chemical processing of the blanket can be accompanied by much lower radioactive losses..

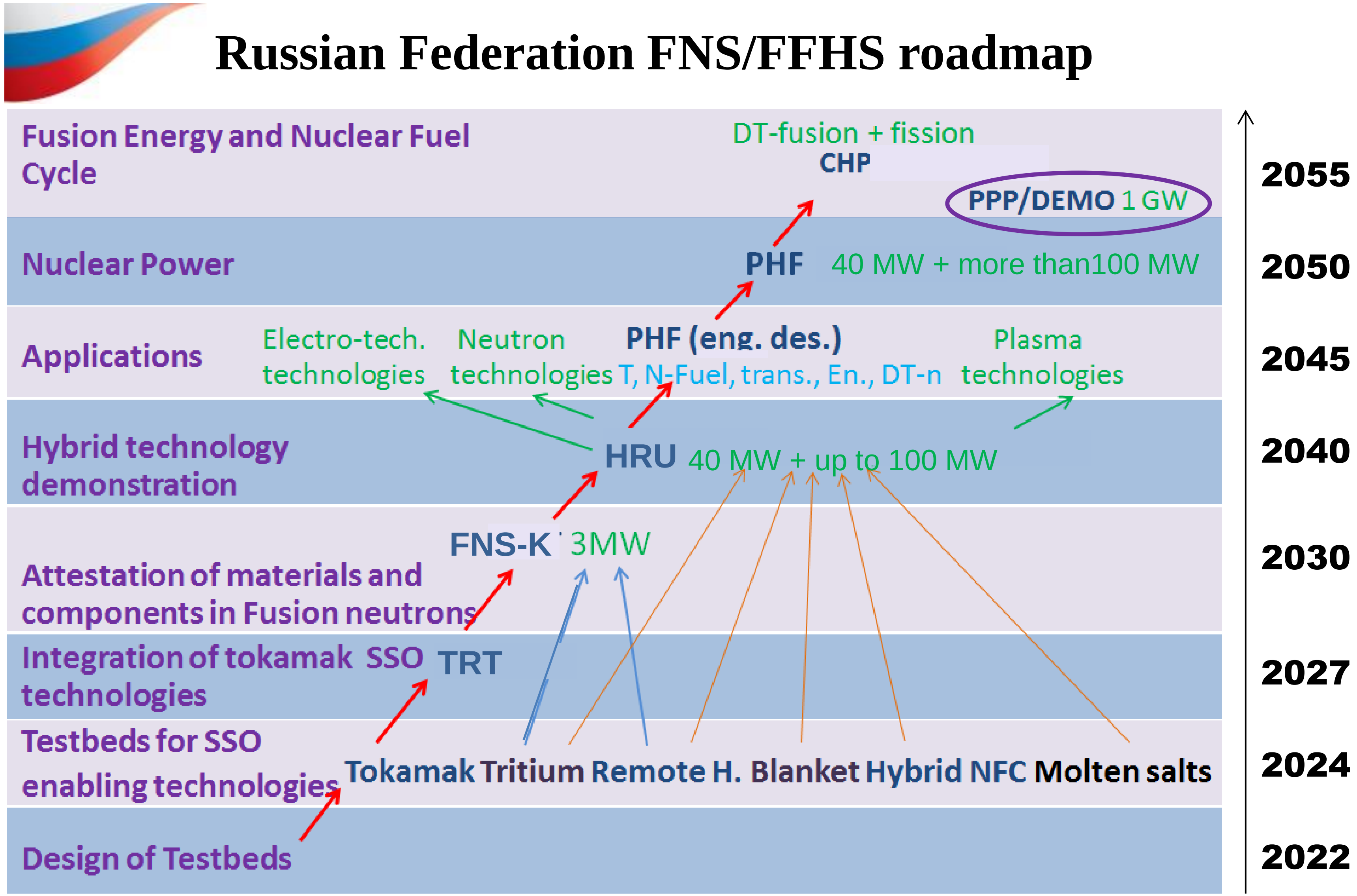
Spent fuel rods will be removed from the reactor core and sent for long-term storage.



Fission reactor 1 GW(e) (3 GW)
Burns (per year) 1088 kg of ^{233}U (and converts 162 kg to ^{234}U)
total 1250 kg
Produces 11.7 kg of **n** of which - 5.4 kg for nuclear fission
- 2.0 kg loss
- 4.3 kg can be at ^{3}H

Of these, you can make up to 13 kg ^{3}H

Strategy for the development of Hybrid Fusion-Fission systems in the Russian Federation



Russian Federation FNS/FFHS roadmap

Fusion Energy and Nuclear Fuel Cycle — DT-fusion + fission, CHP, PPP/DEMO 1 GW

Nuclear Power — PHF 40 MW + more than100 MW

Applications — Electro-tech. technologies; Neutron technologies; PHF (eng. des.) T, N-Fuel, trans., En., DT-n; Plasma technologies

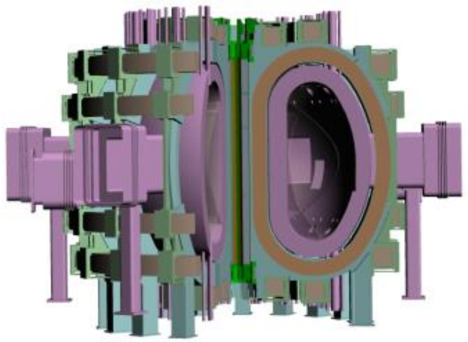
Hybrid technology demonstration — HRU 40 MW + up to 100 MW

Attestation of materials and components in Fusion neutrons — FNS-K 3MW

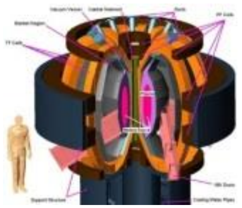
Integration of tokamak SSO technologies — TRT

Testbeds for SSO enabling technologies — Tokamak Tritium Remote H. Blanket Hybrid NFC Molten salts

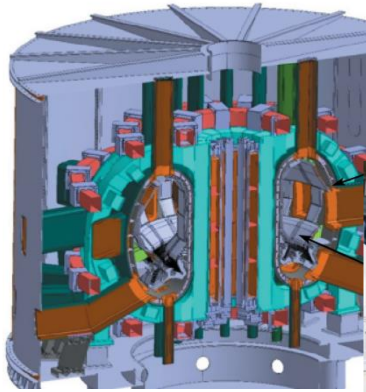
Design of Testbeds



Superconducting magnetic system
40 MW additional heating
40 MW fusion
Integration of nuclear and fusion technologies



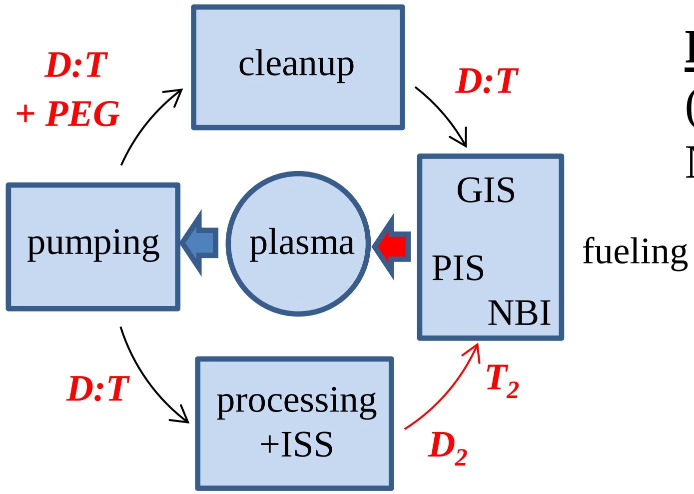
“Warm” magnetic system
10 MW additional heating
3 MW fusion
Stationary tokamak technologies



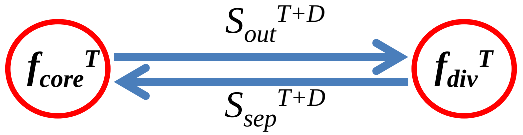
Tokamak with Reactor Technologies

Quasi-steady-state tokamak T-15MD

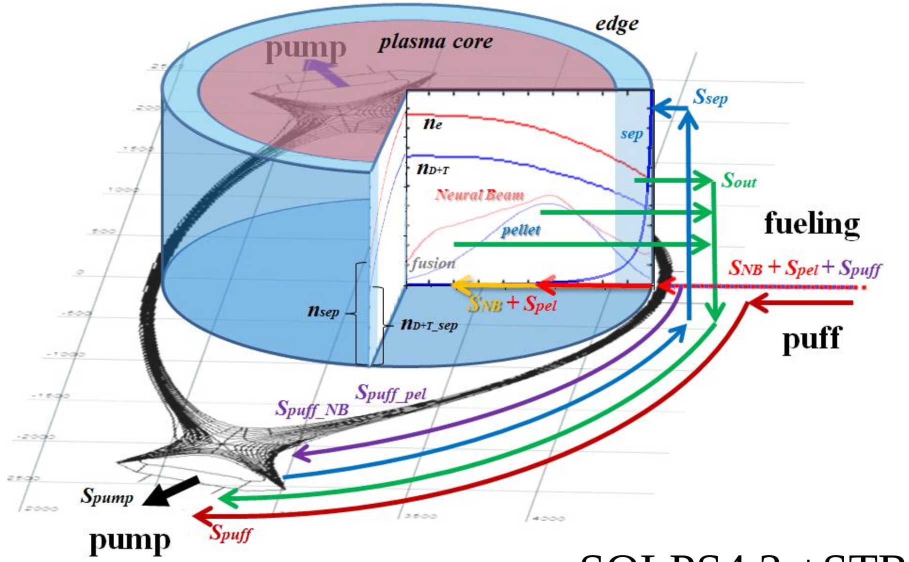
Deuterium-Tritium Fuel Cycle for Fusion (Hybride) Reactor

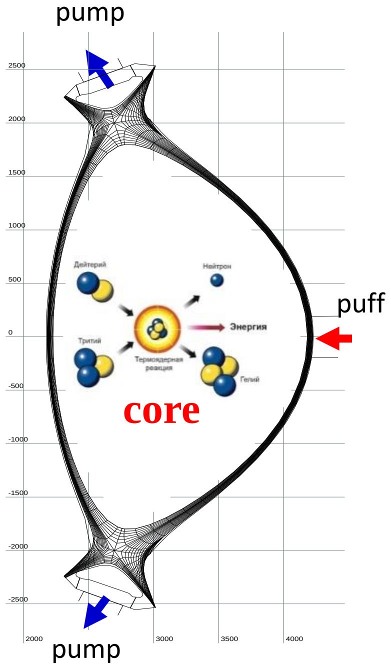


FC-FNS code
(Fuel Cycle for Fusion
Neutron Source)
2014-2022

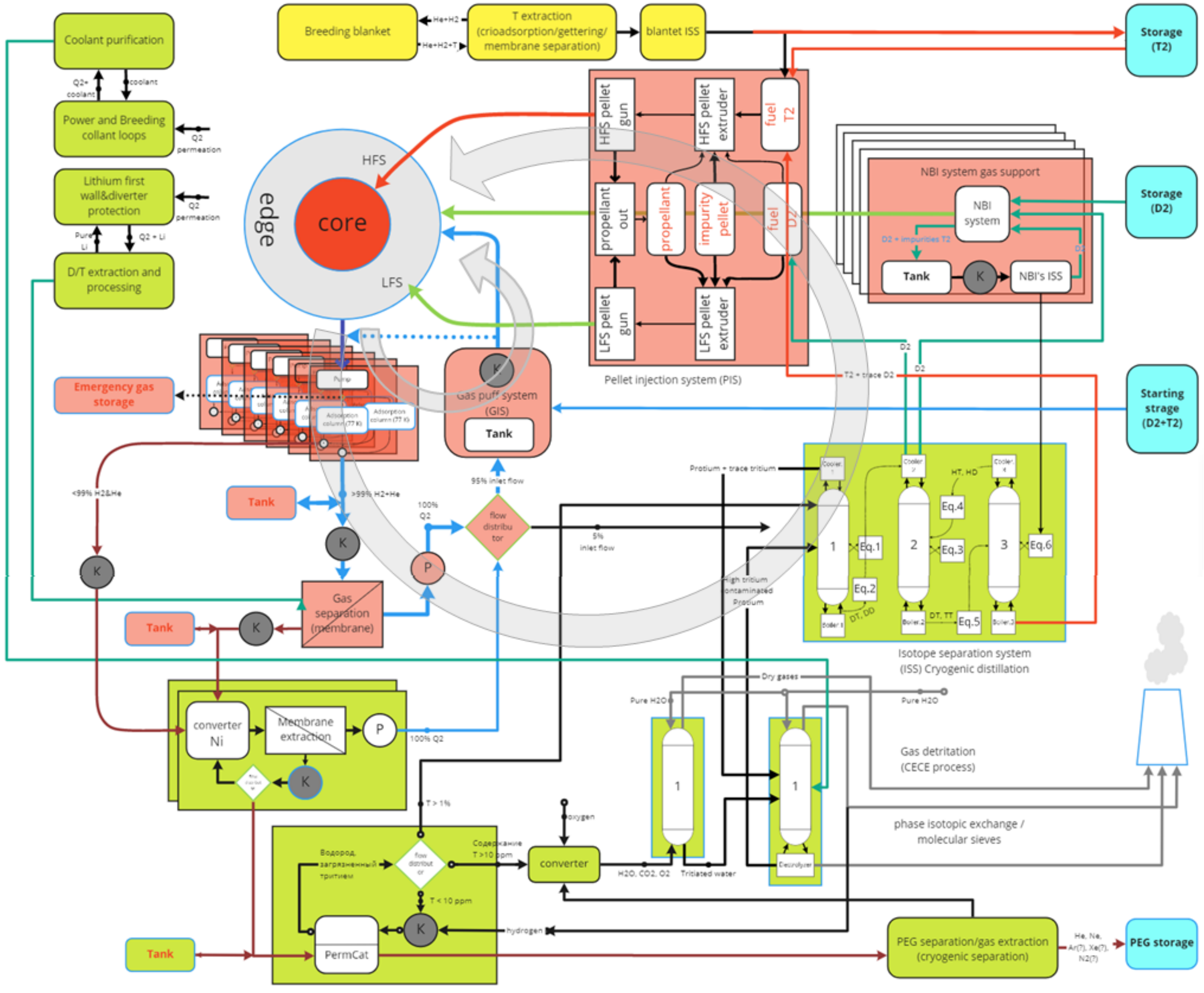


ASTRA+NUBEAM





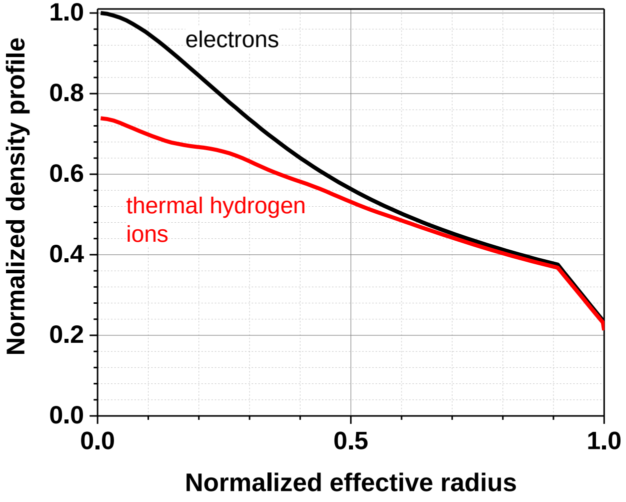
SOLPS4.3.+STRAHL+ASTRA

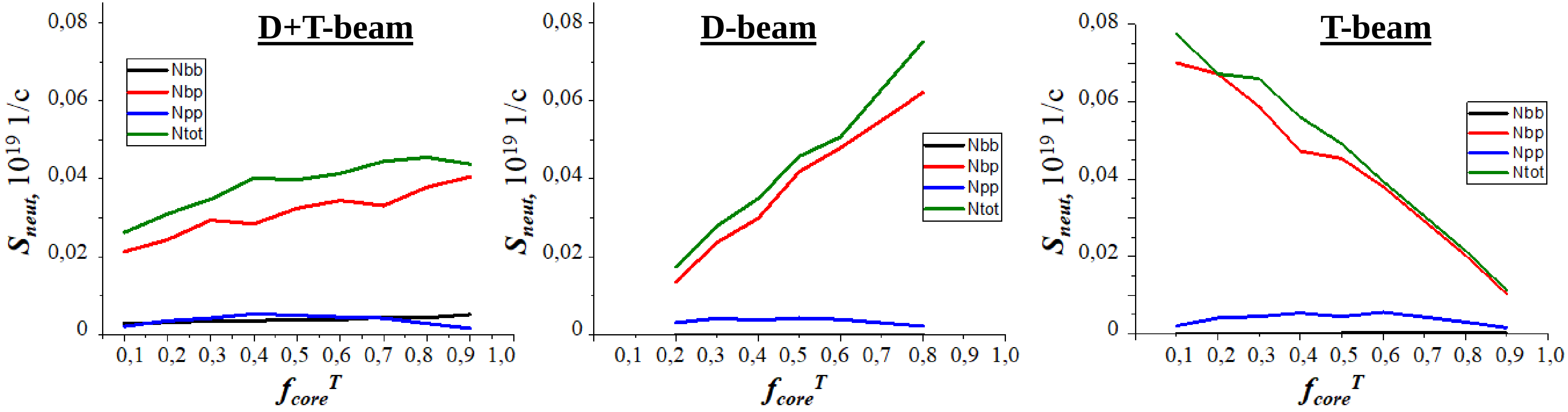


3 contours
(highlighted in
different colors):

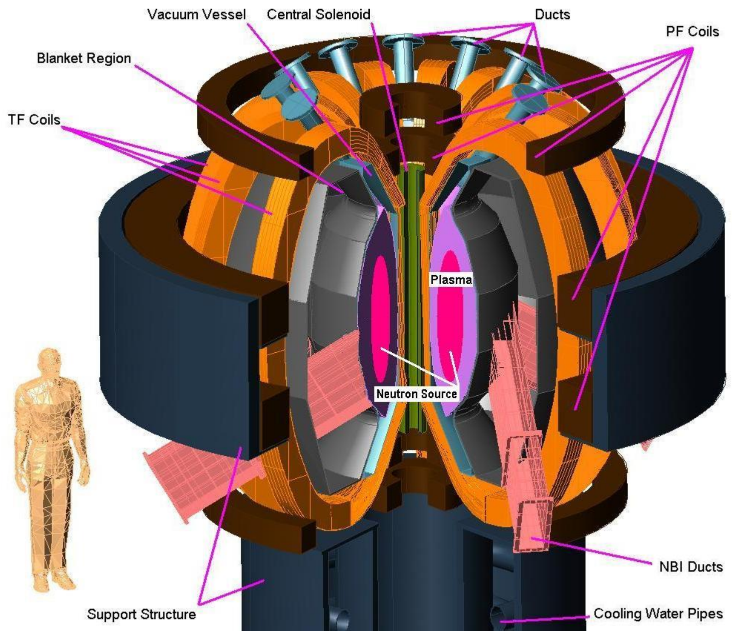
- fast processing of the "exhaust" of the tokamak,
- extraction of T from the blanket,
- processing of T-containing waste

Simulation of a compact fusion neutron source FNS-ST
(isotopic composition of the core plasma and gas of neutral injectors)





Neutron yield depending on the T fraction in the core plasma



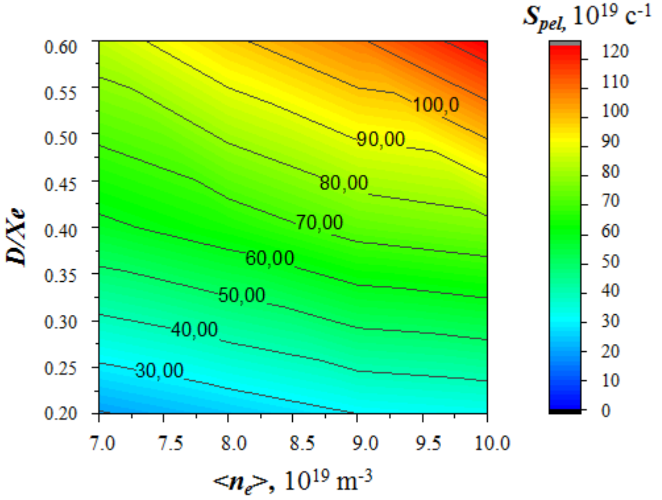
<u>Compact spherical tokamak - features:</u>

- Synthesis proceeds predominantly on beams
- Influence of beam particles on plasma fueling
- Effect of neutrals on plasma fueling

3-4 injectors 3-3.5 MW each

Horizontal injection in the equatorial plane

Total particle flux D+T:

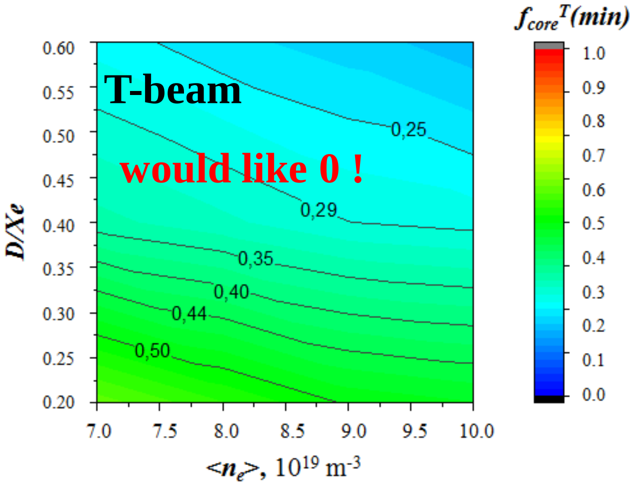


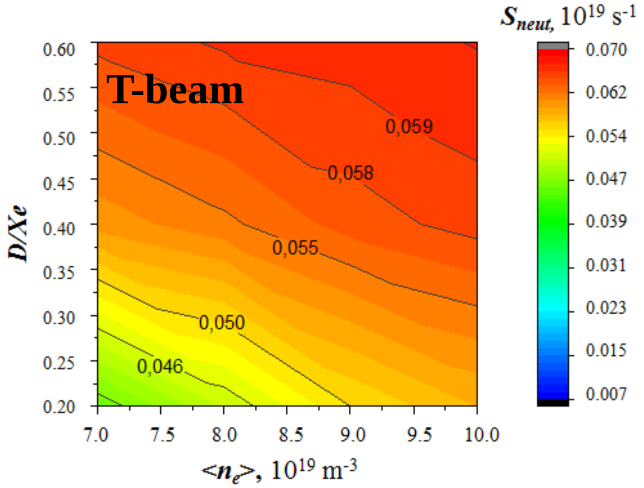
Core plasma and gas of neutral injectors isotopic composition for FNS-ST

Maximum neutron yield:

for T-beam: min value of f_{core}^{T} will be reached at $S_{pel}^{T} = 0$

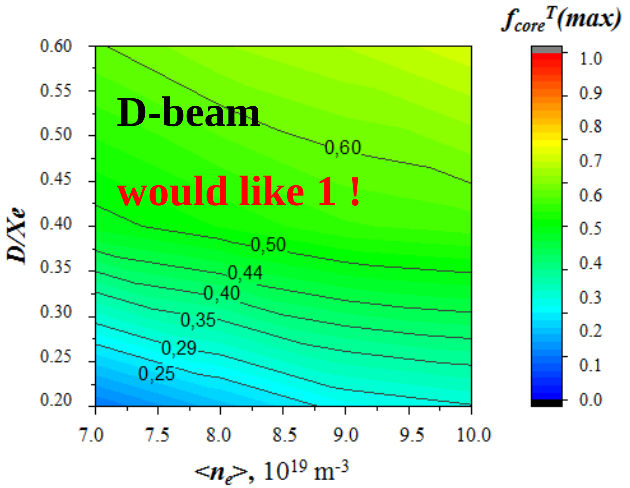
for D-beam: max value of f_{core}^{T} will be reached at $S_{pel}^{D} = 0$

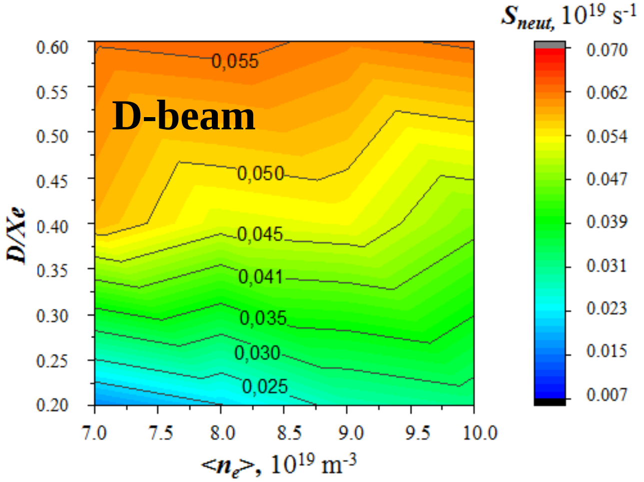




Dependence of the maximum/minimum possible tritium fraction $f_{core}^{T}(max)/(min)$

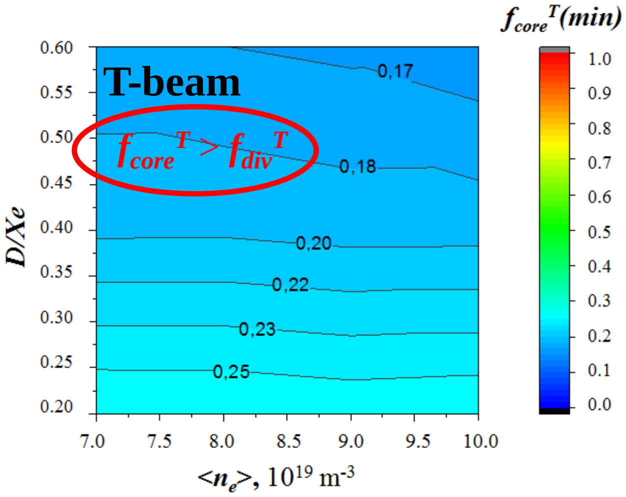
Dependence of the neutron yield S_{neut} for the case $f_{core}^{T} = f_{div}^{T}$

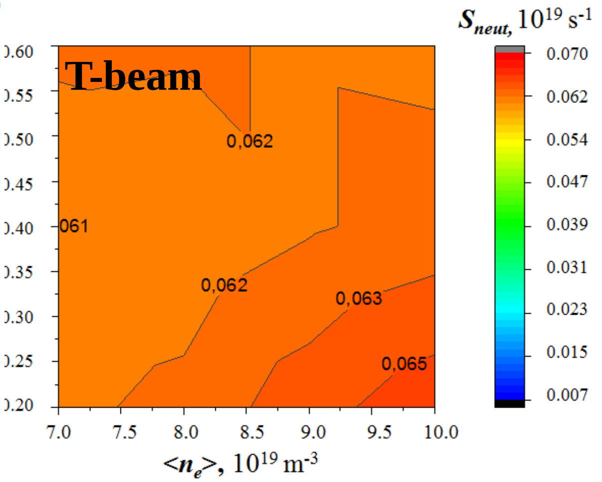




for T-beam: $S_{pel}^{T} = 0$ and $S_{GIS}^{T} = 0$

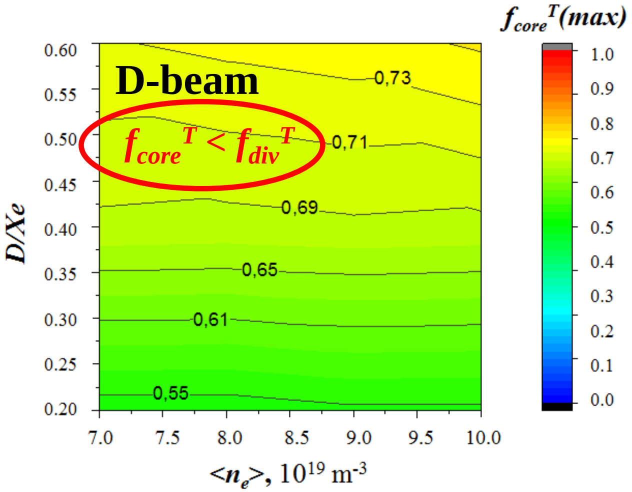
for D-beam: $S_{pel}^{D} = 0$ and $S_{GIS}^{D} = 0$

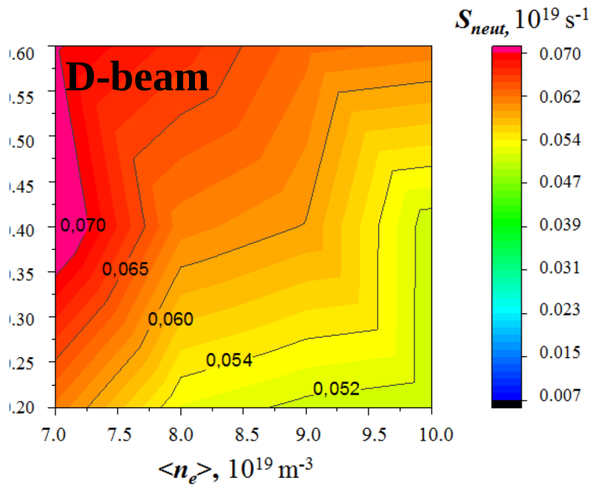




Dependence of the maximum/minimum possible tritium fraction $f_{core}^{T}(max)/(min)$

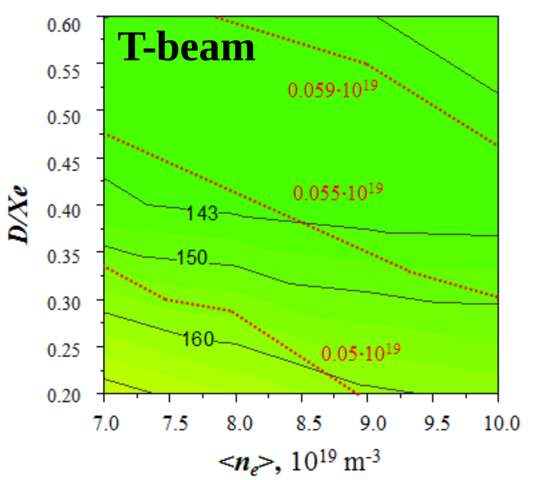
Dependence of the neutron yield S_{neut}

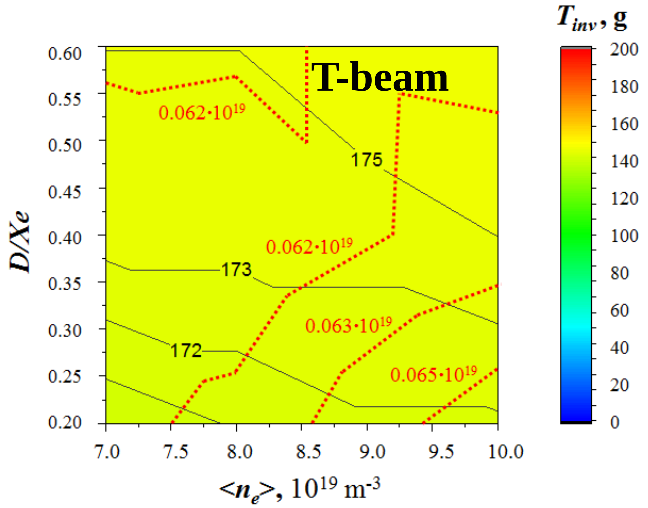


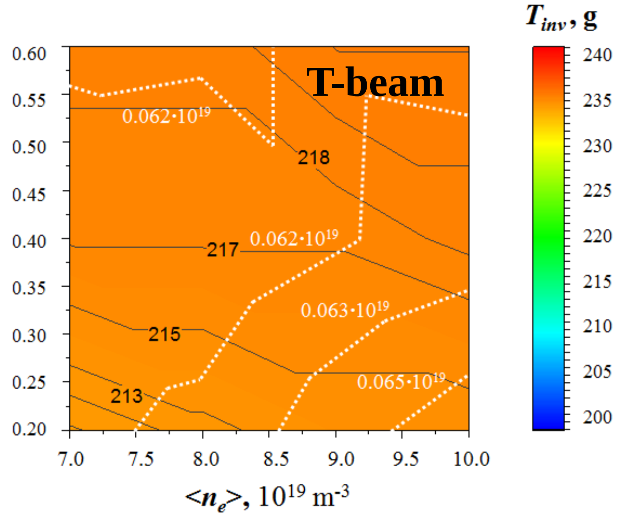


Core plasma and gas of neutral injectors isotopic composition for FNS-ST (new fuel cycle design)

In this scenario, tritium is in the minimum FC systems
(there is no T in gas and pellet injection systems)

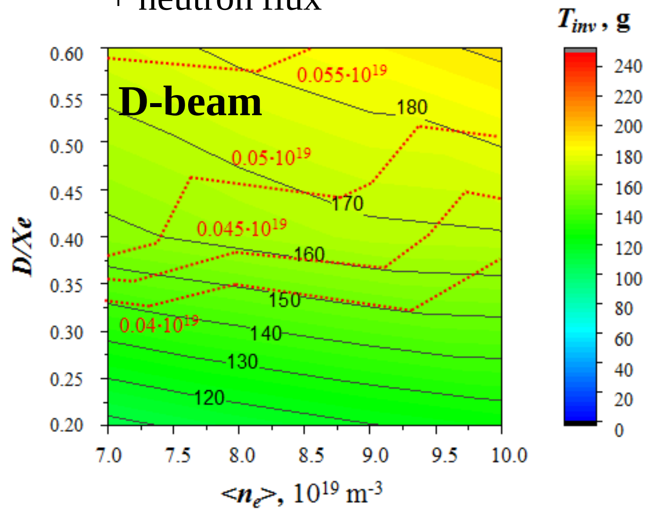




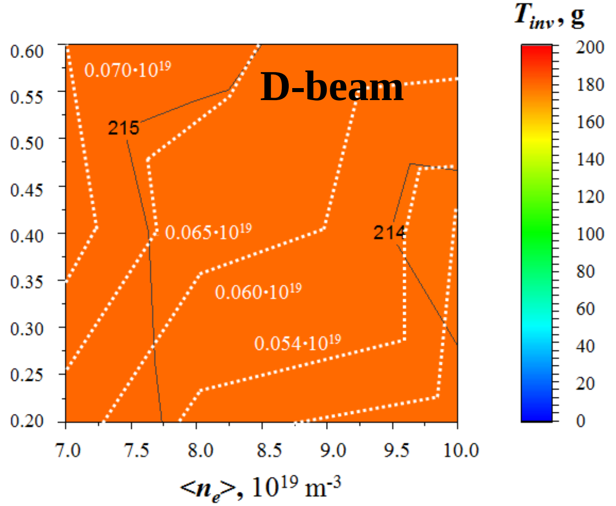


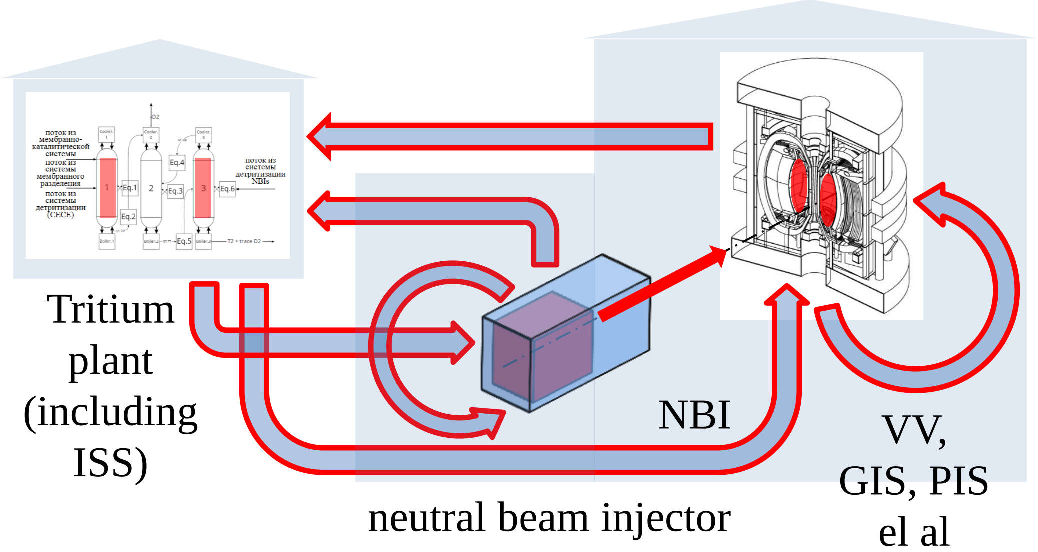
For the T-beam, the scenario of separate NBI gas supply:
T_2 to the ion source and
D_2 to the neutralizer
to create the gas target.

T inventory at the facility site
+ neutron flux



T inventory at the facility site
+ neutron flux





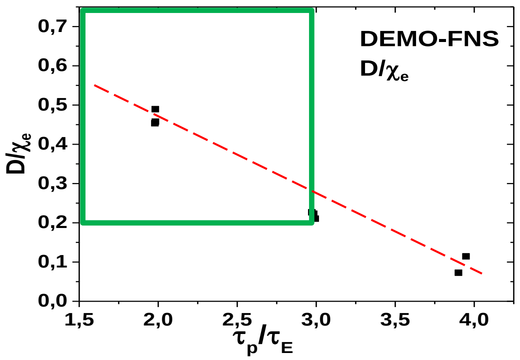
Tritium plant (including ISS)

NBI

VV, GIS, PIS el al

neutral beam injector gas supply

Simulation of a fusion neutron source DEMO-FNS
(T inventory in a facility FC for modes with natural ELMs)

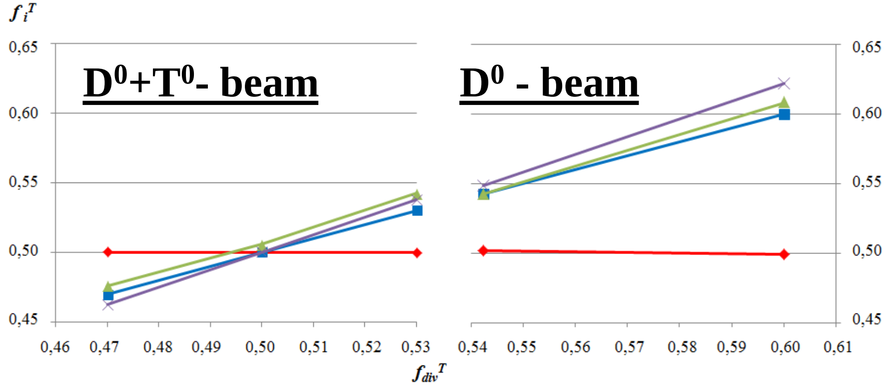


A. Polevoi 2005 ITER:
n* = 0.01-0.7
D/χ_e = 0.2-0.75

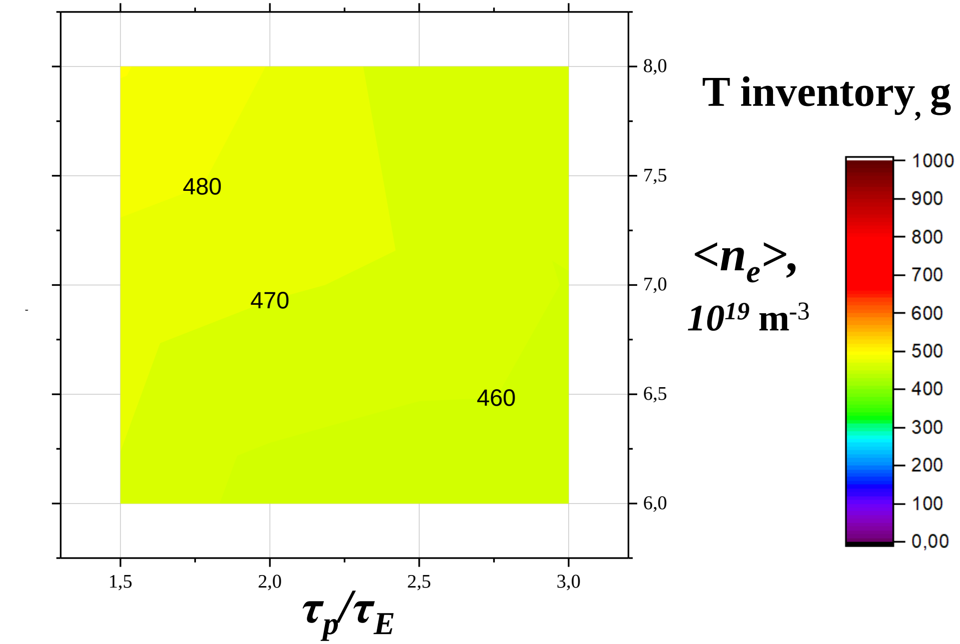
M. Valovic 2005 CTF:
n* ~ 0.1
D_{eff}/χ_e = 0.4

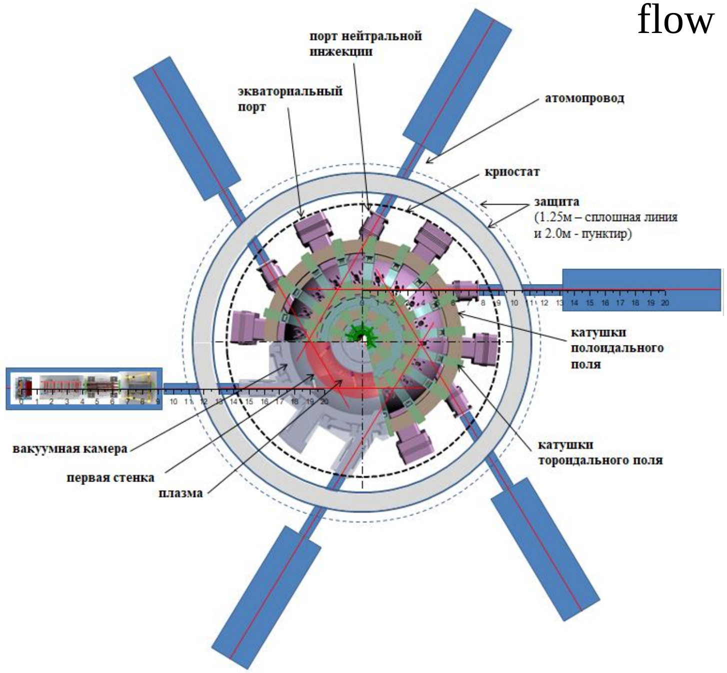
A method was developed to match the isotopic composition of the core $f_{core}{}^T$ and divertor $f_{div}{}^T$ plasma

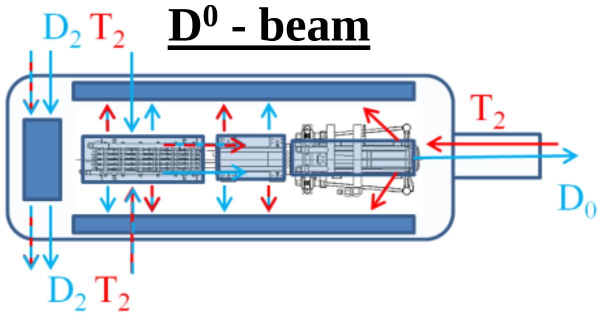
T fraction in plasma and main FC systems



Isotopic composition in key FC systems:
core plasma (🟥), purification system (🟦),
flow distribution (🟩) and gas injection (🟪) vs $f_{div}{}^T$



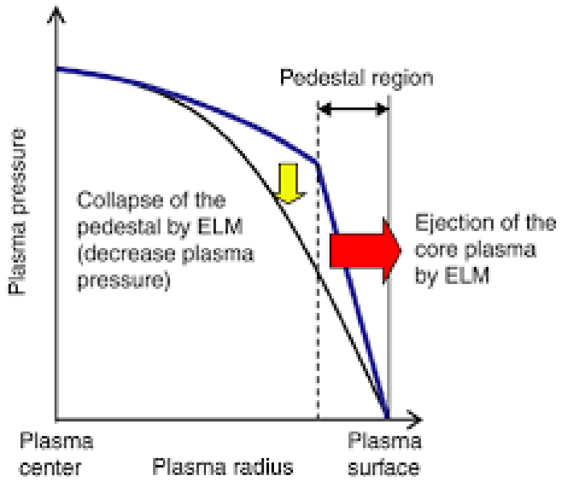




The neutral injection system gas supply

The neutral injection system location on the DEMO-FNS facility

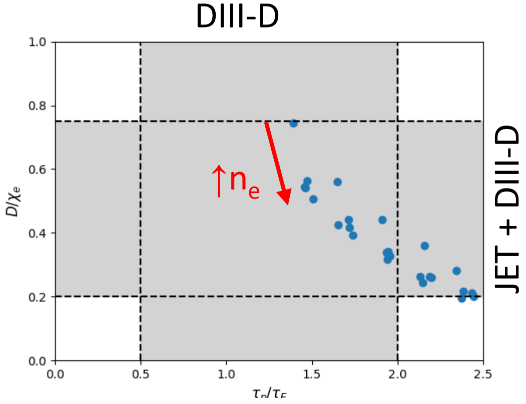
Simulation of modes with convective ELMs in DEMO-FNS

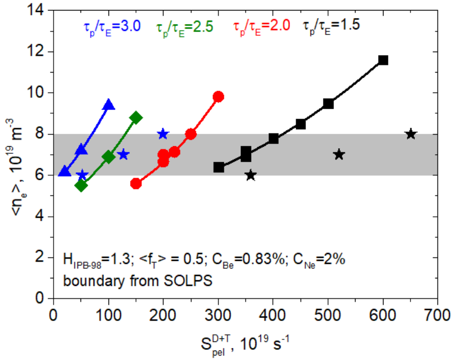


Equation for N_{core}:

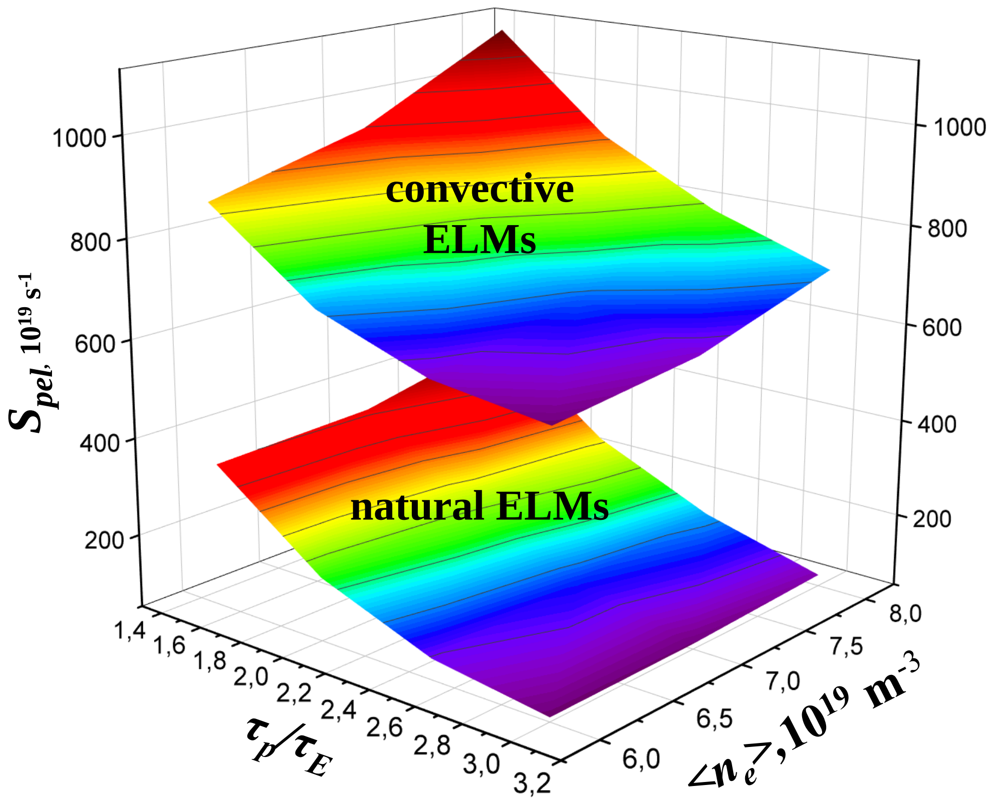
$$N_{core} = N_{sep} + S_{NB}\cdot\tau_{NB} + (S_{pel(LFS)} + S_{pel(HFS)} - \alpha_{ELM}\cdot(1-\gamma)\cdot P_{SOL}/3T_{ped})\cdot\tau_{pel} + S_{sep}\cdot\tau_{sep} - S_{fus}\cdot\tau_{tot}$$ // **FC-FNS** code

From this equation, one can estimate the $(S_{pel(LFS)} + S_{pel(HFS)})$, needed to maintain N_{core} density...

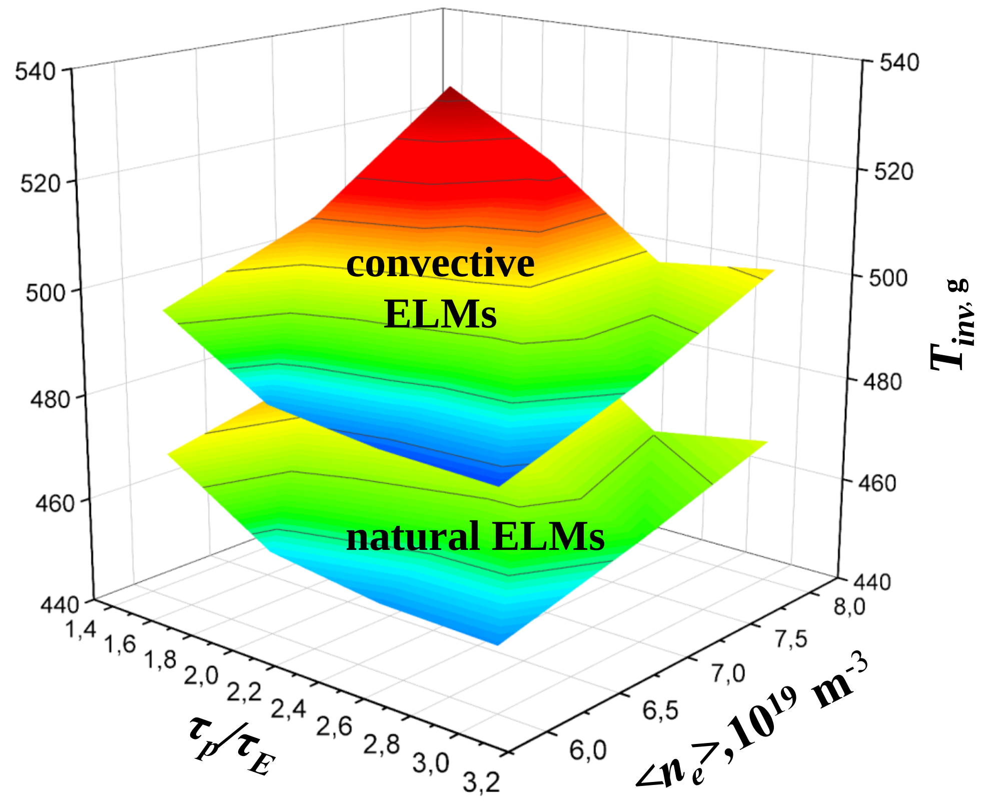




Particle flows from pellet injection and natural/convective ELMs



T inventories in facility FC for natural/convective ELMs



Hybrid Fusion Reactor target indicators in a Fission Reactor power system

Thermal Reactor

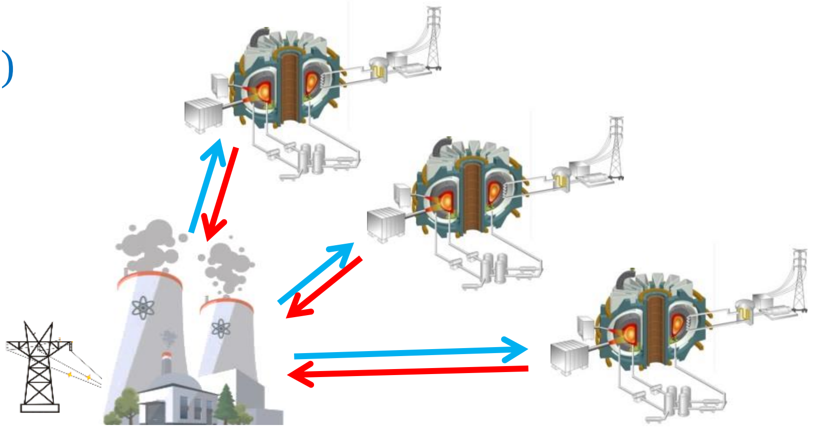
Nuclide consumption – 1251 kg/year (^{233}U)

Nuclide production - up to 13 kg/year (^{3}H)

Energy consumption - 80 MW

Energy production - 3200 MW (thermal)
or 1080 MW(e)

Total to the network – 1000 MW (e)



Hybrid Fusion Reactor (DEMO-FNS)

Nuclide consumption -2.2 kg/year (^{3}H)

Nuclide production – 440 kg/year (^{233}U)

Energy consumption - 200 MW

Energy production: – 80 MW (th)
or 25 MW(e)

***K*- factor**

^{233}U: **1251 kg/440 kg = 2.9**

^{3}H: **13 kg/2.2 kg = 5.5**

HFR+TR to network = (1080+25*2.9) - (80+200*2.9) = 500 MW (e)

DEMO-FNS/HRF

$$\frac{\mathbf{40}\text{ MW }(P_{AH})}{\mathbf{200}\text{ MW}} =$$

(from the network)

efficiency	$Q = 1$	$Q = 2$	$Q = 3$	$Q = 5$
20%	**180/150**	90/65	60/35	35/10
30%	120/90	60/35	40/15	25/0
50%	70/45	35/10	25/0	15/-10

without/taking into account the thermal energy production in the blanket

If we consider the value per source neutron, then the value is TWICE less!

Progress in the field of materials

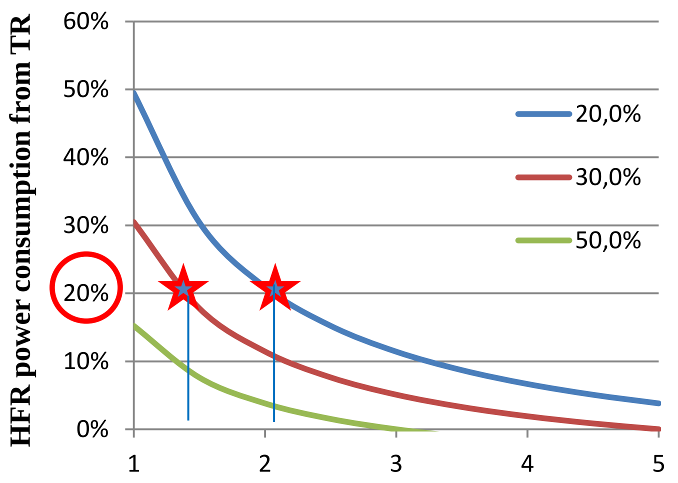
efficiency	$Q = 1$	$Q = 2$	$Q = 3$	$Q = 5$
20%	**70/60**	35/25	25/15	15/5
30%	50/35	25/15	15/5	10/0
50%	30/20	15/5	10/0	5/-5

Tokamak technologies

MeV/n – is the energy spent on obtaining a neutron (fusion) in a blanket

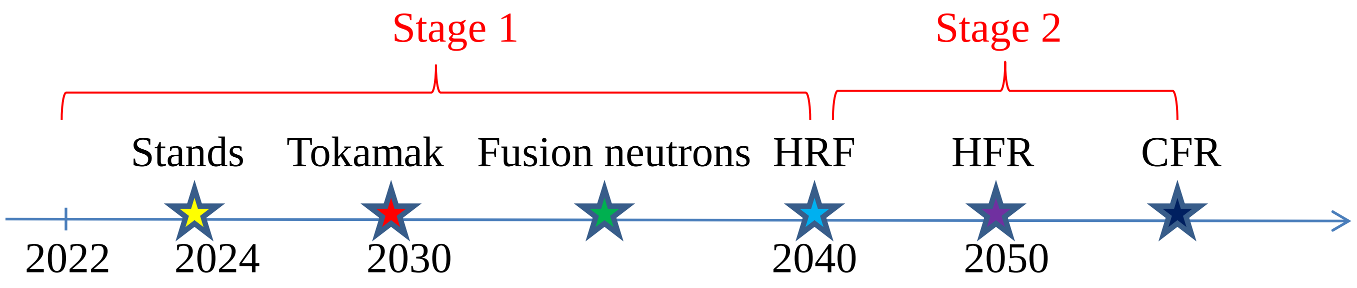
MeV/^{233}U - energy spent to obtain the nucleus of the nuclide (in blanket)

Hybrid Fusion Reactor target indicators in a Fission Reactor power system

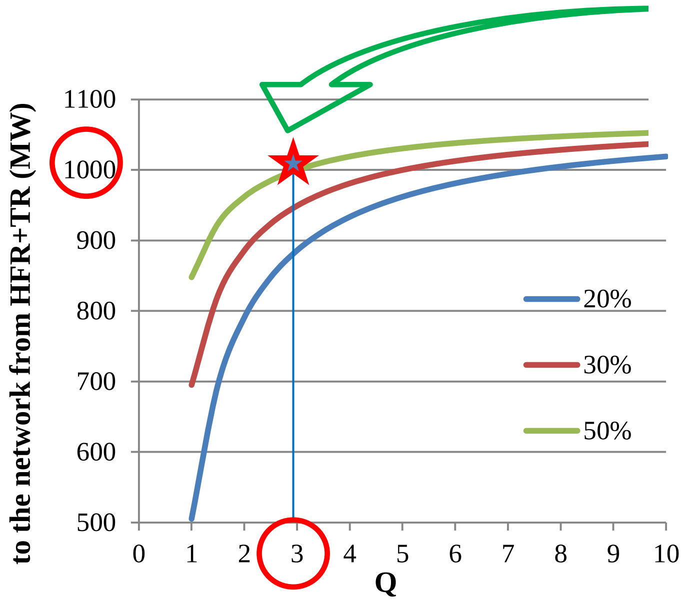


Upon reaching HFR parameters:
Efficiency ~ 30% and Q = 1.5-2(3)
The required targets will be obtained:

- HFR consumption is **about 10%** of the energy produced by HFR (e)
- costs **~ 10 MeV/^{233}U** core (or ~10 MeV/n)


Stage 1
Stage 2
Stands
Tokamak
Fusion neutrons
HRF
HFR
CFR
2022
2024
2030
2040
2050

HFR <u>does not consume</u>
<u>energy</u> from TR!



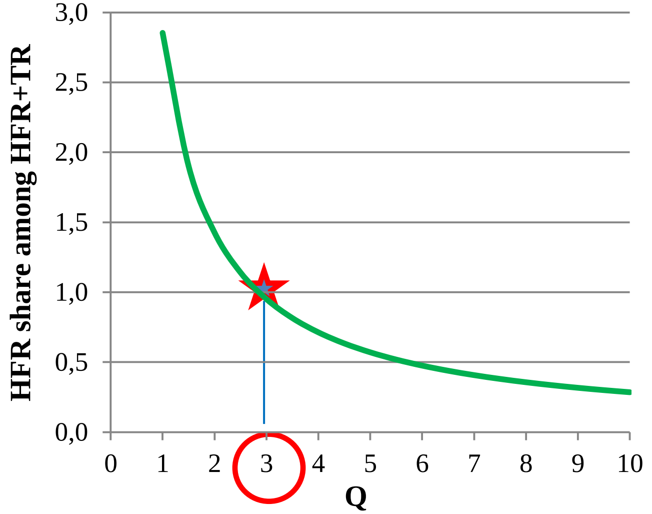
Further improvement of the HFR parameters will contribute to a decrease in the HFR share among HFR+TR
(according to the required quantity)
and grow - in terms of power!

HFR/TR (in pcs):

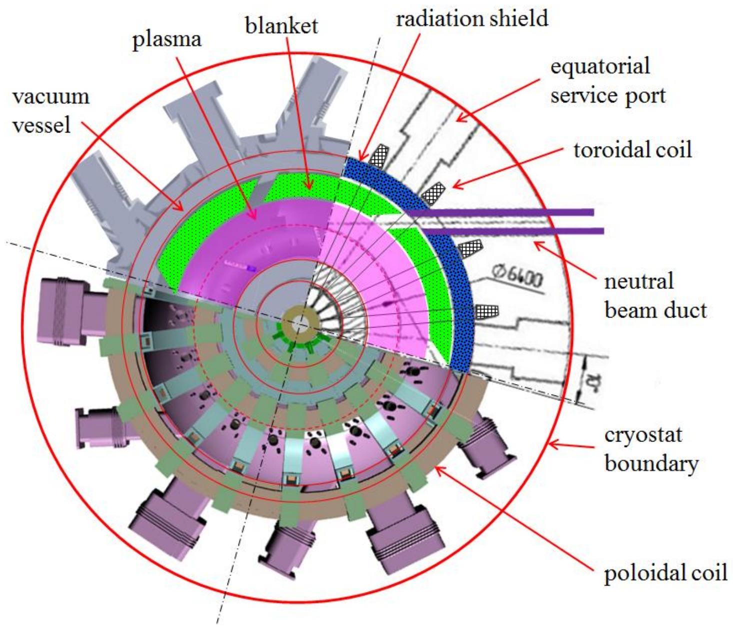
15 % at Q =25
10 % at Q =15

HFR/TR (in MW):

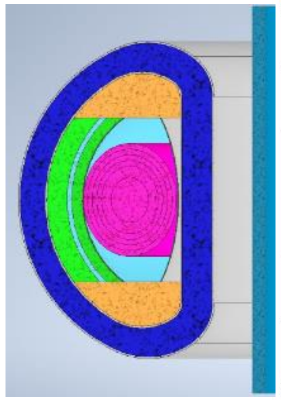
5 % at Q > 15

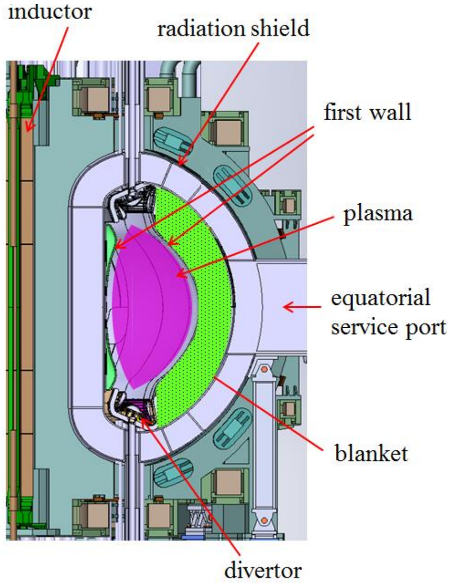


Hybrid Fusion Reactor target indicators in a Fission Reactor power system



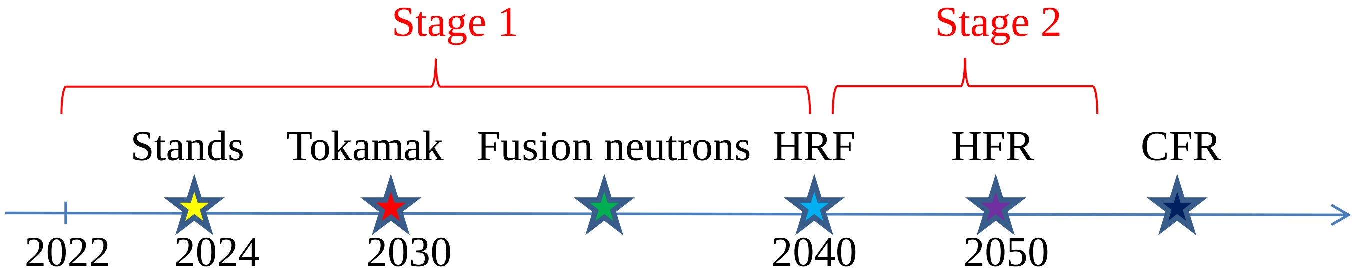
Neutron model



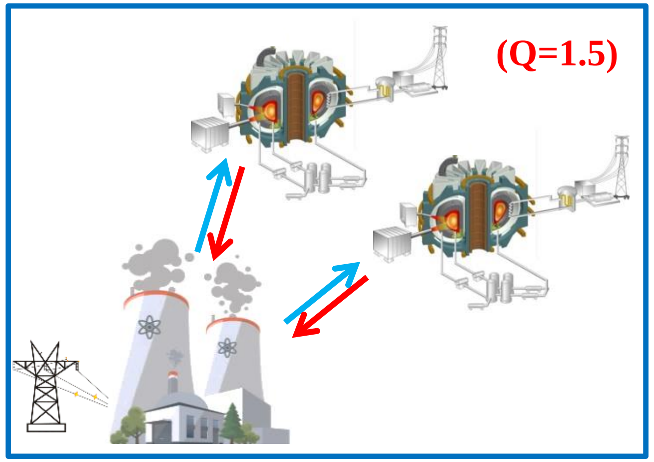


Thus, at the **first stage** of work (on the creation of a HRF demonstration facility within the framework of the RF federal program), target indicators SUFFICIENT for the HFR creation can be obtained!

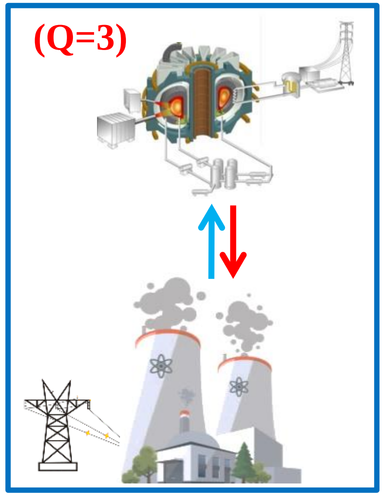
At the second stage of work (following the HRF creation) - to create a prototype of a commercial HFR facility, target indicators should be REVISED in accordance with the CURRENT multicomponent structure of nuclear power (taking into account the evolutionary development of each of the directions of nuclear reactors)



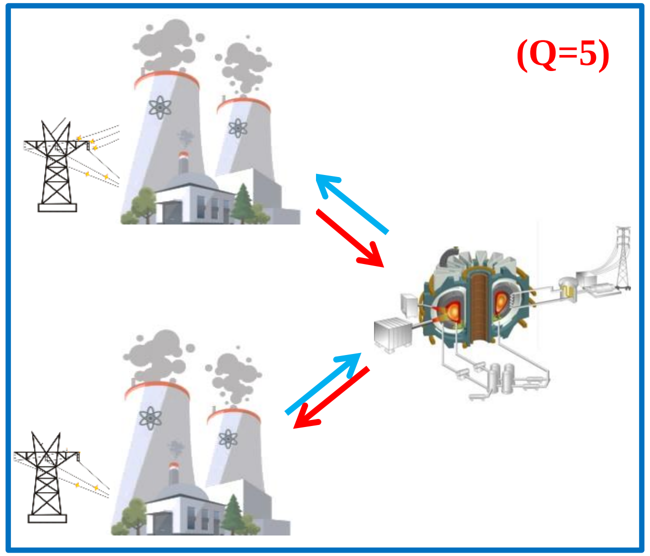
Stage 1
Stage 2
Stands
Tokamak
Fusion neutrons
HRF
HFR
CFR
2022
2024
2030
2040
2050



(Q=1.5)



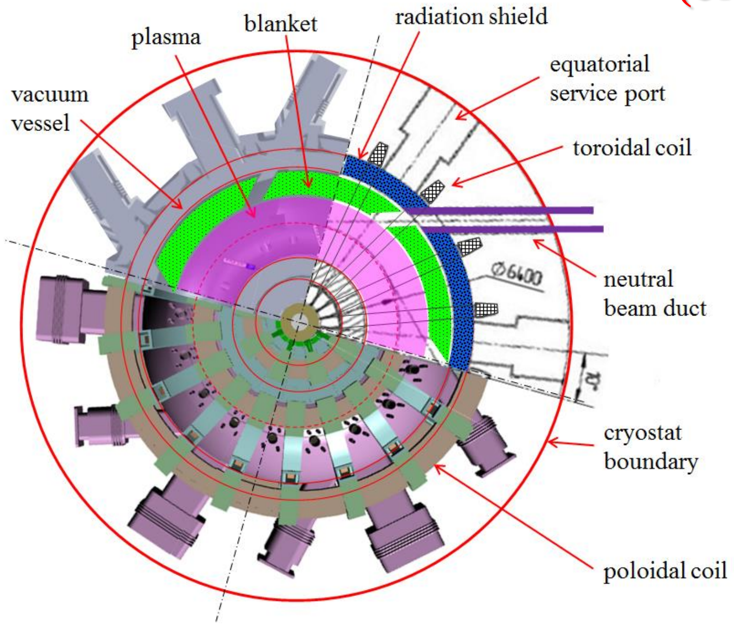
(Q=3)



(Q=5)

S.S. ANANYEV *Ananyev_SS@nrcki.ru*
"The concept of tritium fuel cycle…in the RF"
NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

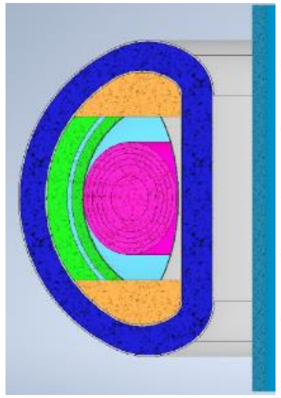
On the issue of forming target indicators for a Hybrid Fusion Reactor

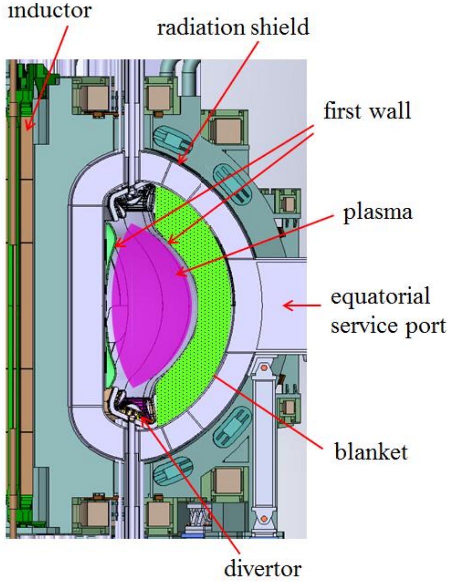


(blanket without multiplier)

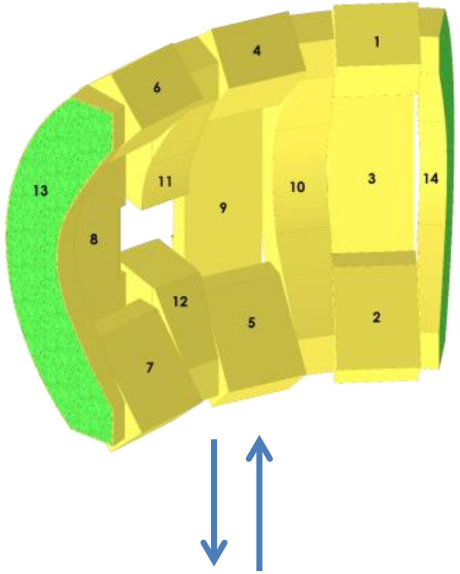
with Be-multiplier

Neutron model



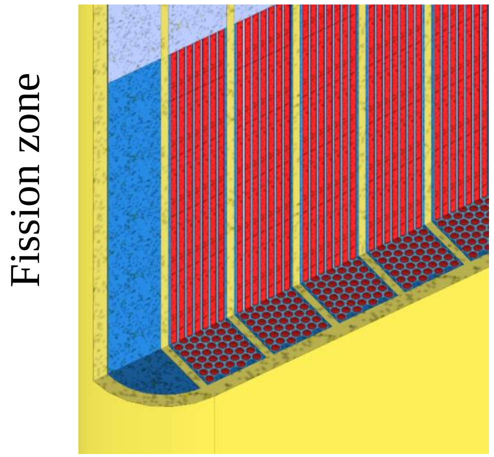


Transmutation zone/
/nuclide production



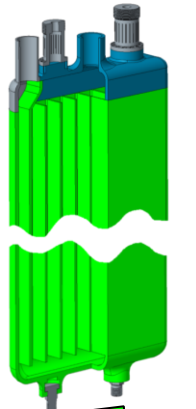
blanket composition turnover for fission/transmutation products extraction

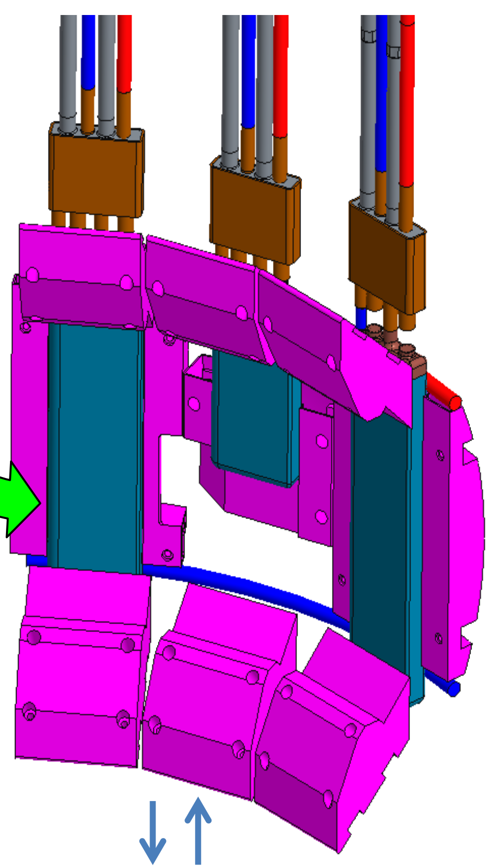
for example, spent nuclear fuel, Pu, MA

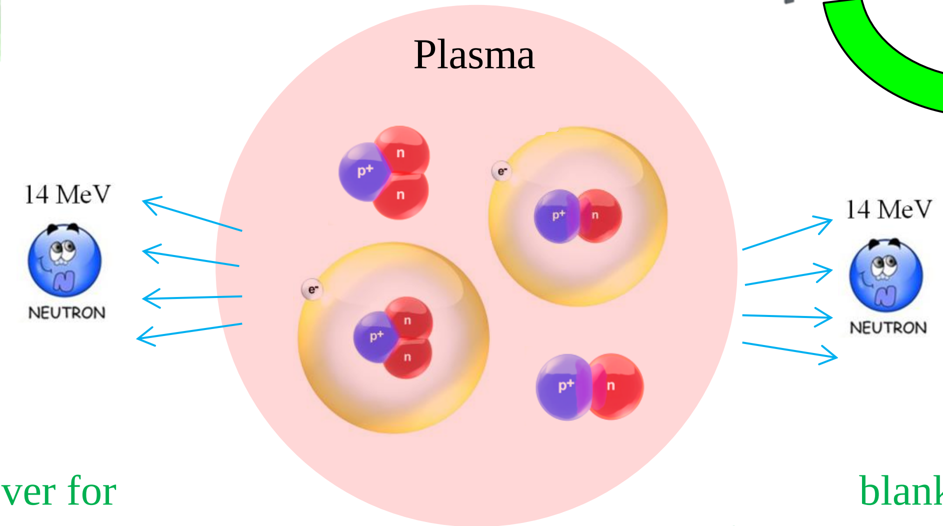


(blanket with multiplier)

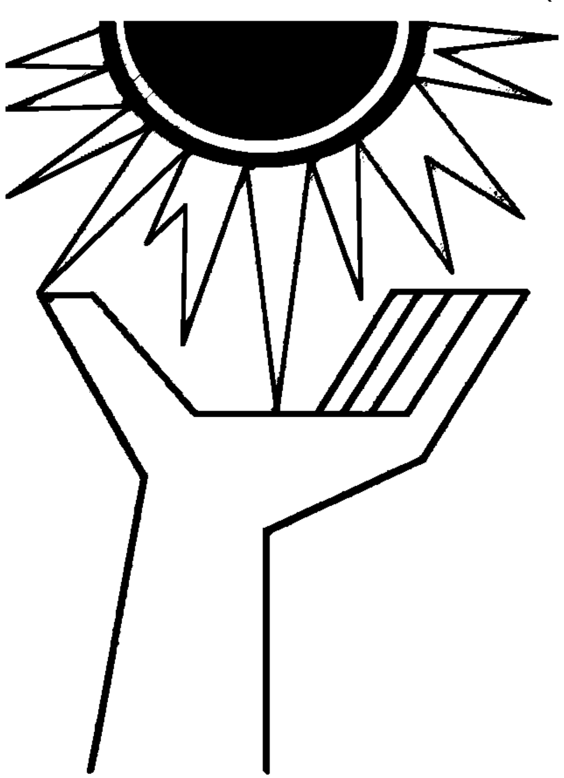
Fuel rods with fissile material that do NOT require processing at the end of work/campaign (!)







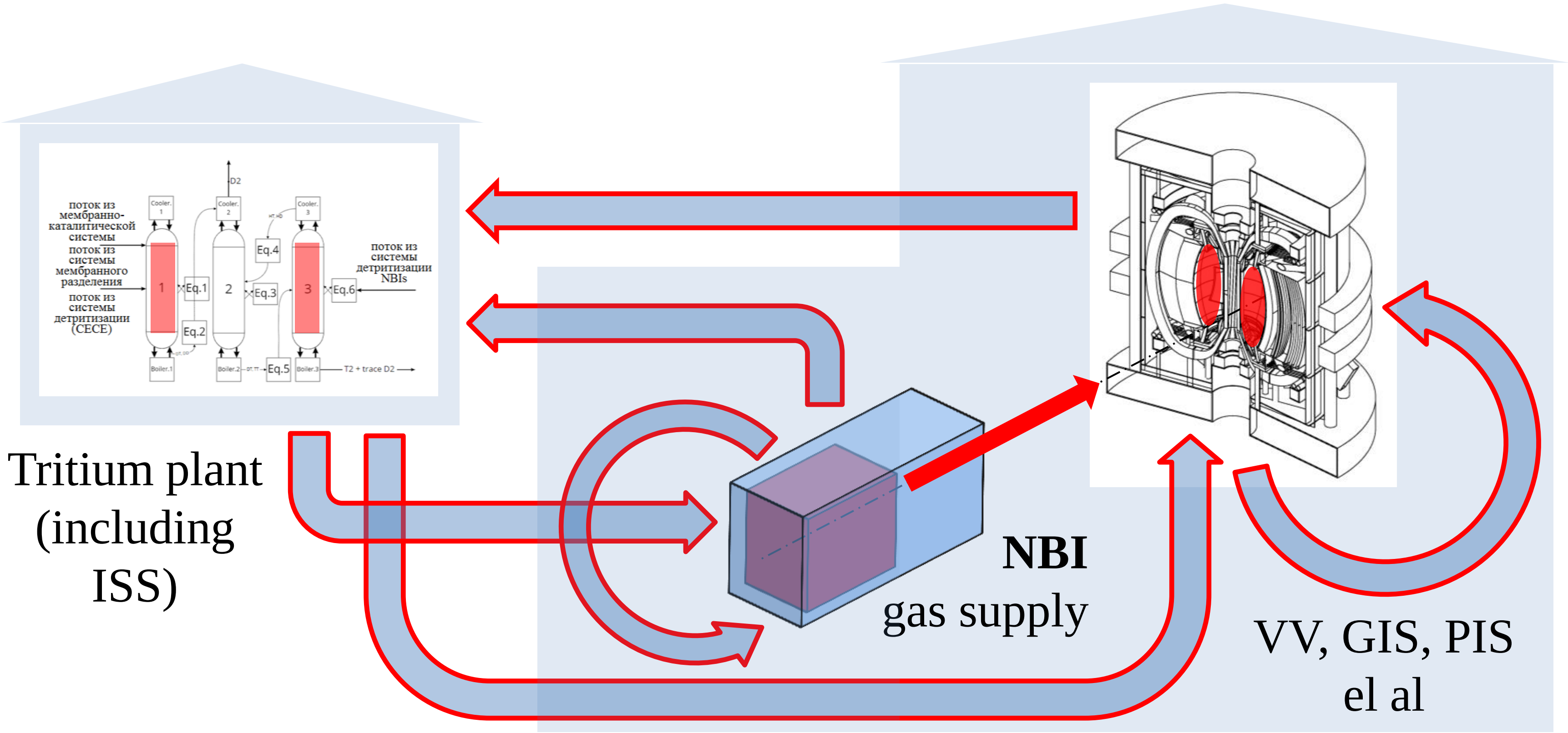
blanket composition turnover for fission/transmutation products extraction



Thank you for your attention!

Note that for making a balanced decision on implementation of a particular scenario, the T_2 inventory in the FC is not the only criterion.

We should also take into account several subsystems with significant T_2 inventory, as well as technological difficulties in implementing the T-beam injection, operating the additional heating system and etc.



Изотопный состав NBI:	T-plant (ISS et al.)	NBIs	VV, GIS, PIS et al.	Total:
D+T – beam	25	20	180	180-220
D – beam (partial separation)	10-25	0	75-160	90-190
D – beam (full separation)	25	0	180	210
T – beam (partial separation)	15	40	60-120	115-175
T – beam (full separation)	15	40	30	90
T – beam (NBI gas support optimization)	60	15	30	110